SIMPLY TAUGHT: CHEMISTRY 1

BY
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PREFACE

This is the first in a series of fundamental Chemistry books that focus on a playful yet factual introduction to basic concepts in Chemistry.

Chemistry plays a major role in society especially in view of the many problems facing the world today such as global warming and the energy crisis. There has never been a better time for Chemists to take center stage in scientific innovation.

This textbook aims to try to inculcate in young (and older) minds a love for the subject that exceeds the desire to simply pass exams and ingrain in them a passion for Chemistry and science at large. It seeks to accomplish this by presenting well known topics in very simple terms that students of all grades (with emphasis on secondary school students) can follow with ease and even teach others in the same simple terms, following a philosophy shared by Richard Feynman in his quote; **"If you can't explain something in simple terms, you don't understand it."** We therefore would be propagating understanding in very simple language in hopes of improving comprehension and properly explaining the concepts presented.

The effort put into this book I ascribe to the idle time spent during the lockdown of 2019, as well as to my wonderful family; Engr. Dr. Mathias Adoyi, Mrs. Helen Adoyi, Dr. Kevin Adoyi and Evans Adoyi. I also dedicate it to my best friend Nnedi Nnamdi-Nwaeze and her family. Lastly, I appreciate all my previous tutors in all the institutions of education I ever attended, especially my lecturers and professors of Chemistry in the University of Abuja.

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CHAPTER 1: ATOMS
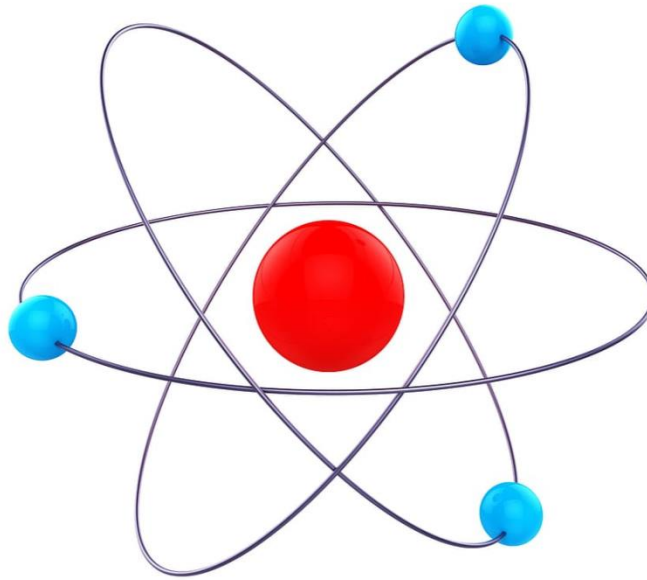
In all the scientific endeavors of mankind none has been quite as revolutionary as the discovery the atom. Indeed it can be argued that the most incredible ideas have stemmed from this field. We are about to dive into a miniature world of particles so small that on the very tip of a needle can be found millions and millions of them. They make up all that we see and despite this appear virtually invisible and can only be observed using very controlled type of experiments. The crazy thing about atoms is that this isn't even the most spectacular feature they possess. We will now delve into their colorful history and note some of these exciting features we talked about. Exams may be tedious but you will be swept away by the world you are about to enter so much that you will be sure to emerge an ecstatic scientist yourself.

A BRIEF HISTORY OF THE ATOM (OR THE MADNESS OF THE ATOM)

One could say the macro world is easily observable and so it is no difficult challenge to observe the things that take place around us except in reality…that would be erroneous. Despite the fact that we can clearly see the things around us we have made several errors when coming to an understanding of these things because they can be difficult to explain. For instance in order to explain lightening the ancient Greeks had adopted the

belief that a superhuman in the heavens threw bolts at the earth, their god they knew as Zeus. The ancient Mesopotamians believed that the sky was held up by pillars as in a temple. Let's fast forward to relatively recent times. It was once believed in the 1800's that lead was a wonder substance and so people used it to make hats, coat plates and even swallow it whole to attain beauty! In relation to the lead craze there is a story about people in England who kept dying from consuming tomatoes. Witches were said to use tomatoes to cause those deaths. It was only realized later that the poor tomatoes were not the culprits, the plates were as they were generously coated with lead. So one can see that even the visible world that we can see and touch can be difficult to examine in its entirety. How then could we possibly study micro particles invisible to the eye? And what's more how did we even come to know about them?

Figure 1-1 "Zeus must be really angry guys!" A Greek man probably once said.

The Greeks who could see the invisible

In many texts on the atom the Greeks are seldom mentioned and it was they who began to observe that something was not quite so obvious in the nature of things. In fact the very word 'atom' finds its origin in Greek text and Greek language as 'atomos' meaning indivisible. So we see that the ancients were certainly keen on an idea here. Up until a few hundred years later the atom was indeed considered indivisible and composing all matter and we must give them credit because figuring that out in as early as 460 BC is extraordinary.

Two of these wise ancients are specifically credited with the discovery of the atom. However, that is only based on the data we have. These two are Leucippus and Democritus, the latter a student of the former. They also added that atoms were of different kinds depending on what properties the matter they made had. For instance the atom of water was considered wet and slippery and iron atoms were metallic with hooks. So we can imagine that the atoms of fire could burn. While this may sound ridiculous to modern day scientists as ourselves we must realize how ancient this was. It was way before Jesus had been born! Nonetheless these theories set more modern scientists on a trail and I emphasize the word 'modern' because from the time the Greeks noted this to more recent times there was little improvement by way of study on the subject but in 1803 that was to change.

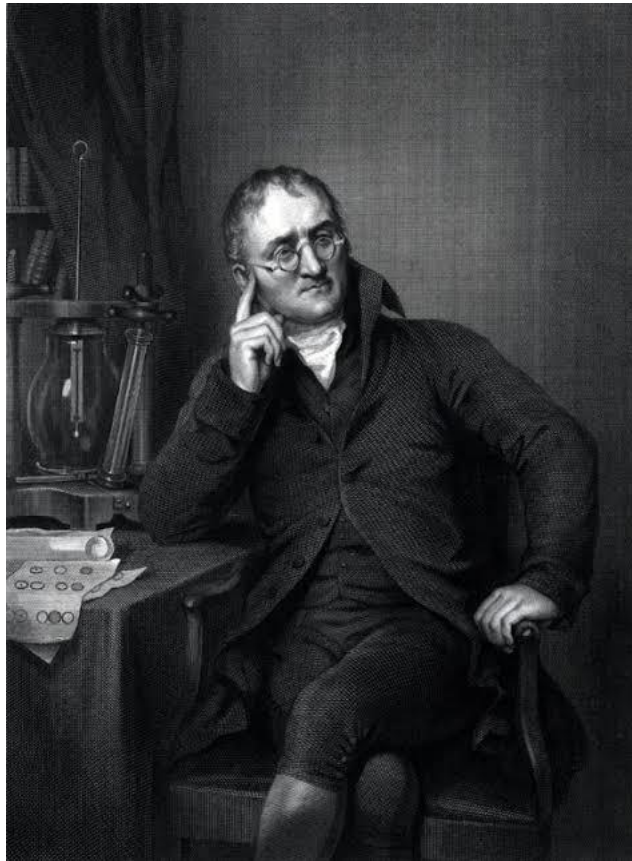## John Dalton, the new Leucippus but not exactly

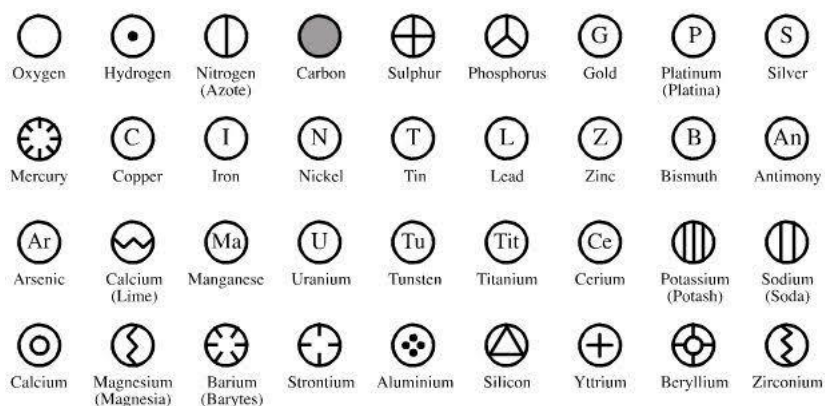**Figure 1-2** John Dalton in a stylish pose

Figure 1-3 John Dalton's symbols for the known elements at the time

A chemist and school teacher who had read the works of the ancient Greeks (most likely) had improved on the works of Leucippus and Democritus stating that atoms were *indivisible, small hard spheres and the atoms of particular elements were identical to each other.* You should hold on to that definition as several points would be ironed out later. He also documented a list of the first chemical symbols of the few discovered elements. He even stated the very first **postulates of the atomic theory:**

1. Matter consists of indivisible particles known as **atoms.**
2. Atoms of the same element show similarities in all ways but differ from atoms of other elements.
3. Atoms can neither be created nor destroyed.
4. When atoms combine, they do so in simple whole number ratios to form compounds.
5. The atom is the smallest unit of matter that can participate in a chemical reaction.

So there we have it. The above postulates are the very basis on which modern chemistry is built and we are only just getting started. Before we move on it would help if you stick to this definition for the time being:

"The atom is the smallest unit of matter that can participate in a chemical reaction."

You'd thank me later.

The boom of the 1900's

Okay technically it began in the late 1800's. We are not entirely certain what John Dalton did in addition to the discoveries he made but he seemed to do something extra like maybe set off an investigation bomb because almost right after his study everyone wanted to gain in on the atom action. It was discovery after discovery and I am sure that if social media existed our phones would have been 'blown' from the overwhelming wealth of new discoveries. Walk with me.

Beginning at the end of the 1800's in the year 1897, we see a studiously engaged Joseph John (J.J) Thompson bent over a cathode ray tube and inspecting it. He has just made a tremendous discovery. He has discovered that unlike what our ancient Greeks and John Dalton believed the atom isn't indivisible. It can be divided and on this 'division' we notice a negatively charged particle of significant mass which he called a 'corpuscle' and we are glad that name did not catch on. However it was a most significant breakthrough. Below is an image showing how this experiment was conducted and don't worry we will walk through the process carefully and I'll have to explain because I am sure Thompson won't have the time (He's second guessing the name).
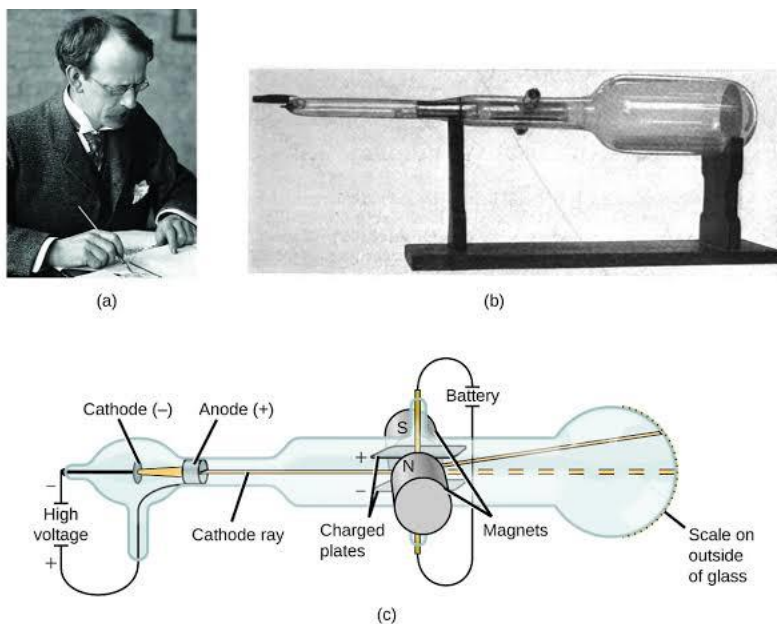

Figure 1-4(a) J.J Thomson, (b) the actual cathode ray tube used, (c) A schematic showing how it works.

Before diving into the discovery of the electron, let's come to understand and appreciate the cathode ray tube. As seen in the image above a cathode ray tube is well, a tube. It is a tube made of glass and with wires connected at its ends. Within the glass

compartment is a vacuum (meaning all the air is pumped out) and an electric charge passes through the tube forming a glow.

Before Thompson's experiment many people had known about the cathode ray tube and the glow (rays) produced. Thompson however wondered if this ray was all there was to notice. He then decided to customize a cathode ray tube, adding charged plates on either end. The plates were then given two slits that connected to a scale outside the glass which could be used to measure charge as shown above. On applying a magnetic field across his fine tube he noticed something incredible. The rays had deviated from the straight path. What this showed was that the charge had been affected by the magnetic field.

"So the ray and the charge are as intertwined as pizza and cheese." He said probably, stroking his chin. (He didn't.)

What he had just discovered was that the 'rays' were actually particles as they could be affected by a magnetic field. Further experiments showed that these 'corpuscles' which we would rather call 'electrons' were relatively light(lighter than hydrogen, the lightest element) as well as negatively charged.He later put forward a model of what he conceived the atom to be, and no it had no metal hooks as the ancient Greeks thought instead it was a positively charged sphere with electrons embedded.
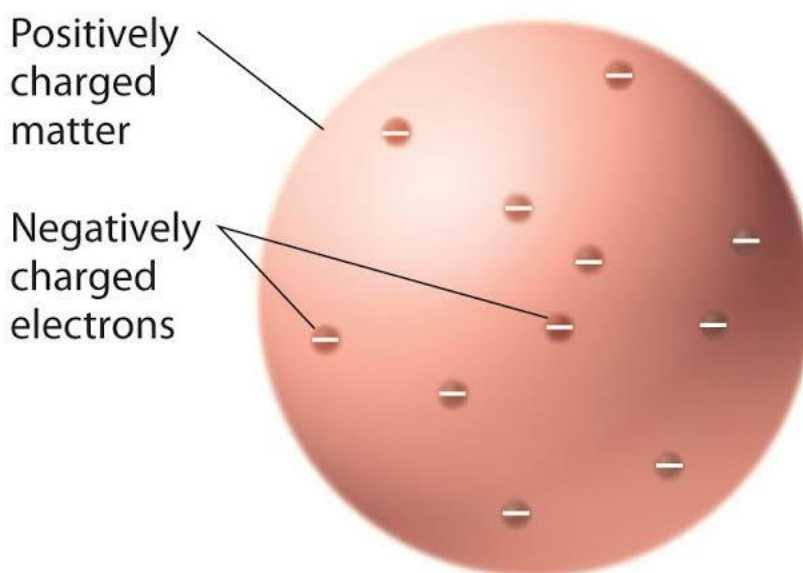

Figure 1-5 The J.J Thomson model of the atom.

This won him the 1906 Nobel Prize which he rightly deserved. So we have met the electron and we should hold on to an important property of it.

"Electrons are negatively charged particles."

Rutherford Shoots Gold

I still believe this was quite an expensive experiment and you may just agree. Just like Leucippus and Democritus, Ernest Rutherford worked and studied under J.J Thomson. His mentor and teacher had probed into just the surface of the atom and he caught some of that atom fever. In the 1911 experiment which he performed with two of his colleagues Geiger and Marsden, he fired alpha particles at thin sheets of gold foil. Now, alpha particles would be discussed later under radioactivity but what you should know now is that these particles are positive and positive charges are repelled by other positive charges but attracted to negative charges. In addition, alpha particles are quite heavy so it'll take a lot to deflect them off their course. So walk with me.

Figure 1-6 Ernest Rutherford

Now, if the atom is a sphere of positive charge as Thomson observed, we should expect that the fired alpha particles would pass through the gold foil sheet (alpha particles are so tiny, they could) and show little to no deflection but this well, was not the case and we can see the surprise on Rutherford's face. Can you see it? I see it every time I mentally walk by him.

Turns out that most of the alpha particles fired passed through the gold foil. This was not something to make him widen his gaze at the screen, but then the unexpected happened. A few of those particles became deflected but not just deflected, deflected at alarming angles as though the footballer Messi had kicked them hard. We can now walk over to the desk of the great man and bend over his shoulders. In his notes we can see that he is describing the experiment; "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." Extraordinary. It is

certainly not something anyone should try but I can't imagine shooting a tissue paper with a gun and expecting the bullet to come back and hit me but then I suppose it is probably more economical than firing gold. Rutherford's interpretation of this experiment was that unlike what his mentor had postulated, the atom was not all positively dispersed charged but the charge was concentrated in the middle, a small very dense centre known as the nucleus and the atom itself is mostly composed of empty space. This was such an astounding discovery especially as it happened in only a few years since Thomson's incredible studies. Rutherford naturally had to make some changes to the existing idea of what the atom looked like based on Thomson's work.
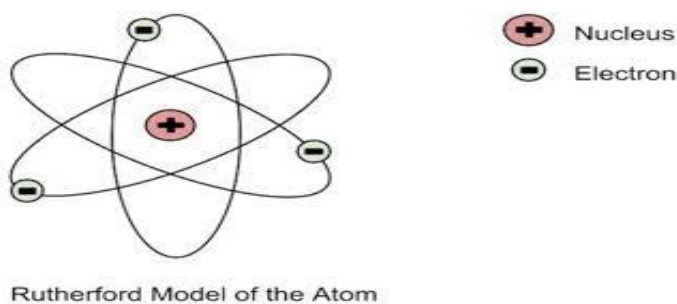

Figure 1-7 Rutherford's atom.

He proposed that the electrons orbited the positively charged nucleus that was situated at the center of the atom.

"The nucleus is the positively charged center of the atom, composed of protons."

Niels Bohr on another level

Thomson and Rutherford were great scientists and everyone knew that but despite how significant their studies were something was just not quite right. According to fundamental scientific laws, spiraling electrons should not remain spiraling around the nucleus and should crash pretty soon like a jet engine in the air out of fuel but Rutherford's atomic model could not explain this. It wasn't magic that kept electrons

moving about and someone had to find out what. Then in came Niels Bohr and now it's time to walk with me.

We enter a room and find the man facing a board. We see strange drawings just like the ones below.
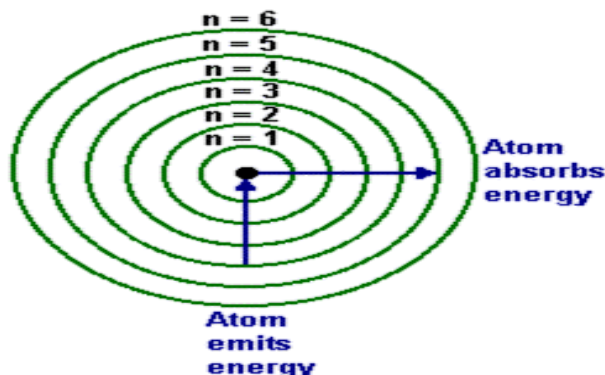

Figure 1-8 Atomic energy levels.

He seems to be frantically writing so I'll explain what is going on. You have probably heard about quantum theory. No? Well it is another of those insane little concepts that have been conceived because the atom is just so strange. It was brought about by a man named Max Plank, who observed in an experiment that radiation was carried in 'packets' called *quanta.* Don't leave just yet, stay with me. We would explain quanta in a while but for now just picture indomie packets. Each packet can only hold so much indomie and not more. Energy according to Max plank was not an indefinite stream as was believed by most but 'indomie packets' of energy instead.

The work of Niels Bohr was based on this concept. He noted that the reason the electrons did not 'crash and burn' into the nucleus was that the electrons could only be located on particular energy levels. So the energy of electrons was quantized or could be said to fit into particular 'electron indomie packets' -which sounds like a good name for a new indomie package. Electrons couldn't just assume any random value but had to remain at these levels and could only move between them. If an electron had acquired energy (maybe due to heating) it could 'jump' to a higher energy level but on releasing that energy it would fall back to its energy state. The ground state or ground level was defined as the lowest energy level an electron could go as you can see in the image above.

At this point in this amazing history we could go on to a happily ever after moment and say that everything was fine and that Bohr was the hero of the day, the last avenger who stood up to Thanos and defeated him (Get the reference?) but unfortunately that is seldom the case in the story of the atom. When scientists thought they cracked a code,

they only opened it to find more puzzling problems. The atom has well become a miniature Pandora 's Box.

Niels Bohr's model worked amazingly when applied to the hydrogen atom, but when scientists began involving heavier elements they found more and more complications. We would explain these complications a little later. For now, we should remember that we cannot underestimate the work of Niels Bohr because it helps us understand chemistry at least at the fundamental level. A thorough grasp of Niels Bohr's atomic model is a grasp of chemical bonding and reactivity rates of elements in the periodic table. Since the aim of this text is to narrate the history leading to our present knowledge of the atom, walk with me as we strive to get to the Standard Model of the Atom.

Schrodinger traps a cat

Of course the atomic Pandora's Box had only just begun.After Niels Bohr had taken a crack at this atom wonder, another scientist by the name of Erwin Schrodinger became infected with the fever and set to work trying to straighten out the rumples of Bohr's atom. In 1926 he proposed that electrons instead of being imagined as particles should be pictured as waves instead. He used a plethora of equations to explain this and ended up with a picture of the electrons not as distinct particles but as *electron clouds.* As much as we would love to go into his study and watch him work on coming up with these equations, I'd rather not and am sure you won't want to either, at least not just yet. Chemistry unfolds in layers and soon even Schrodinger's equations would be nothing to fret over.

Figure 1-9 Erwin Schrodinger
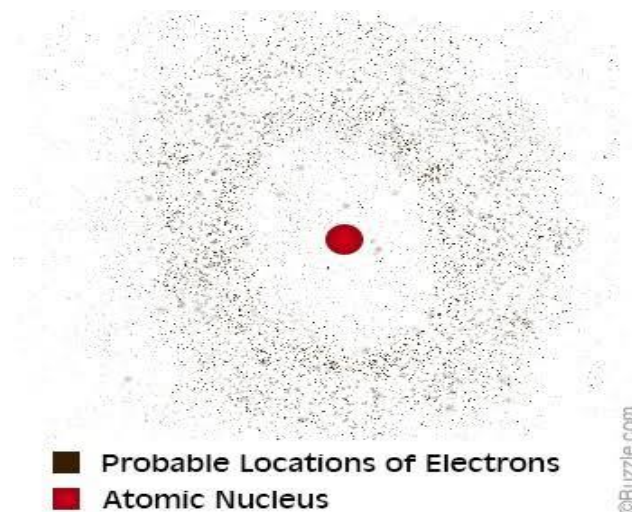
Figure 1-10 The electron cloud

Nonetheless Schrodinger showed that the clouds were only just estimates of the electron's position because we can't really tell where the electrons are. We can only guess likely areas where we may find them. I think this makes sense because you can imagine losing a small marble in a large cotton candy cloud of identical small marbles. Good luck finding it. These areas where electrons may likely be found have been called electron orbitals. You certainly would not want to forget this.

"Electron orbitals are regions within an atom where an electron would most likely be found."

We'd talk about this really soon.

Now I know what you're thinking. What does all this have to do with a cat and a box? Well, just like Schrodinger's equations, it is safe to say that that is well beyond our scope at least for now but remain curious and you'd find out.

James Chadwick, the other Democritus

So after J.J Thomson had discovered the electron and proposed his model of the atom and Ernest Rutherford, a student of his discovered the nucleus and proposed his own model of the atom, the 'atom breaking boys' were far from done as a third person in the line, a student of Ernest Rutherford discovered an important part of the atom, one that would have made John Dalton take back some points in his postulates if he had known about it. The student was James Chadwick and that discovery is the neutron. It has no charge (neutral) and shares the nucleus with the proton, while the electron surrounds it.

"The neutron has no charge."

With the discovery of the nucleus came the knowledge that unlike John Dalton's postulate, atoms of an element could *differ* based on the number of neutrons they possess. This is called **Isotopy.**Before you understand isotopy however, you must come to terms with the concepts of atomic and mass numbers.

"Atomic number is the number of protons in the nucleus of an atom."

The atomic number was observed to be the reason for the characteristics an element possessed.

"Mass number is the number of protons and neutrons in the nucleus of an atom."

And now…

"Isotopy is the existence of atoms that have the same atomic numbers but different molecular masses (mass numbers) due to a difference in the number of neutrons."

And now, we could paint a complete picture of the nature of the atom, but not just yet.

The Standard Model

If you thought the atom was crazy, think again as crazy is an understatement. Most secondary level textbooks don't venture into this area but we are hardened scientists and we would cut through the thick jungle until we arrive at our treasure or at least have a glimpse of it, which is the aim of this section.

The standard Model came into the scene in as recent as the 1970's. After all the craziness of the atom scientists continued to dig deeper and deeper but no matter how much digging was done they continued to meet hard ground. Nonetheless the effort was seldom futile as more discoveries opened up the atom's mysteries. The chart below shows the particles of the standard model.
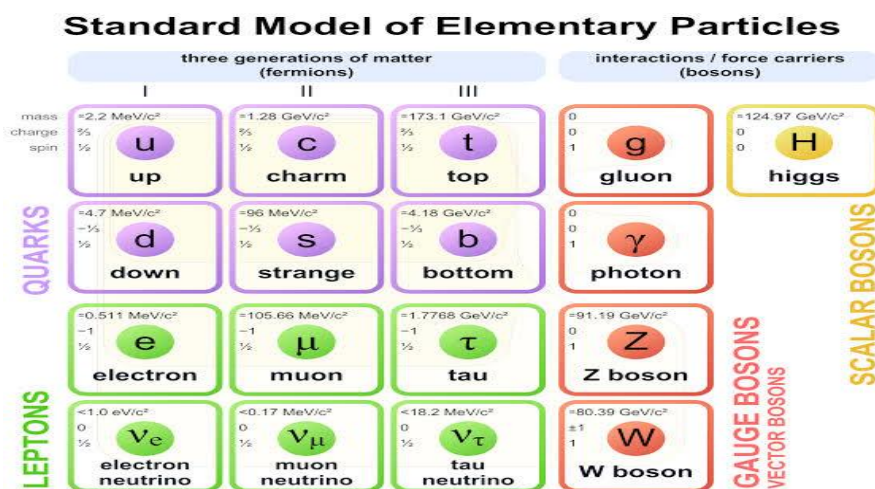

Figure 1-11 Standard Model chart.

According to this model a number of particles explain how the world and the universe work. These are fermions, bosons, quarks, leptons, anti-quarks…. It may seem like a lot

to take in. Why not drop down this book for a quick, refreshing cold drink first and come back in a bit so that we walk through the standard model, at least briefly?

Back to briefly exploring the Standard Model

Hope you are hydrated and well rested now because you are going to need quite the effort to grasp some of the final madness of the atom. Don't worry it isn't hard, you've just got to exercise some imagination.

We seemed to be speaking a strange language a while back. I mean electrons, protons and neutrons we could manage but fermions? Bosons? Queen Elizabeth? Now that's too much but remember that all the high sounding words are actually easy when you get to know them. So don't fret, but enjoy what you learn.

"Knowledge which is acquired under compulsion, obtains no hold on the mind." –Plato

With Plato's guiding words, let's begin.

The standard model is the most recent advance towards deducing the nature of atoms. In time the atom fever became even more intense. A lot of money was pumped into research in order to understand whatever was going on because it seemed that the atom would never be short of mysteries. The atom went from being the simple model to one that required quantum mechanics to understand. Several questions went unanswered. One of these was, "*What holds the protons together in the nucleus when they should pull apart having the same charge?"* Even the neutron could not completely account for this. As time passed several other particles were observed in a plethora of

experiments. The **photon** was then added to these fundamental particles, described by the famous Albert Einstein, followed by the **positron** observed by Anderson then the **pion** (holds the nucleus together, answering our initial question) by Yukawa, the **muon** by I.I Rabi and the list went on until hundreds of these basic particles were discovered. I can only imagine what schooling would be like if you were asked to list these particles. Quite sure I just may have dropped out because that won't be funny.

After decades and decades of work the overwhelming number of these fundamental particles became more concise, easy to manage and kept me in school. These particles make up the Standard Model as you have seen in the table above. They are only a few and their interactions and compositions are summarized in the image below.
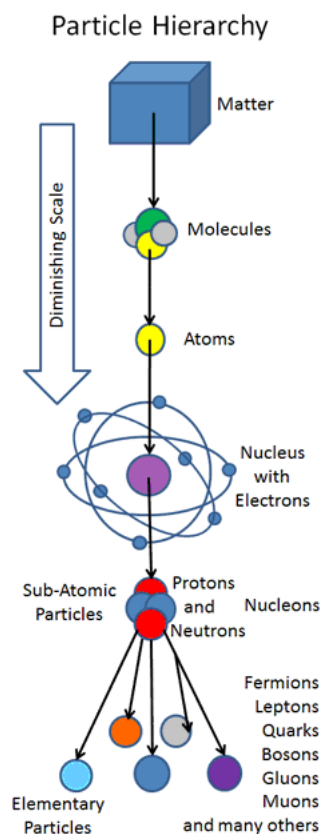

Figure 1-12 Relation between the Standard Model particles.

This concludes a brief history of the atom and yes it is brief because on account of our scope quite some information was left out. Don't stop being curious however and don't get tired because we've got quite a long, interesting way ahead of us.

SUMMARY:

- The ancient Greeks were the first to juggle with the concept of an atom. They called it 'atomos' meaning indivisible. Leucippus and his student Democritus are credited with the discovery.

- In 1803 John Dalton published the first postulates of the atomic theory and proposed symbols for the known chemical elements at the time.

- Joseph John Thomson discovered the electron in his cathode ray tube experiment, he observed that they are negatively charged and proposed the structure of the atom to be a positively charged sphere with electrons embedded like a pie with resins.

- Ernest Rutherford who was a student of J.J Thomson discovered the nucleus of the atom in an experiment and learnt that the atom is mostly empty space. His model of the atom was a dense, central nucleus with electrons spiraling around it.

- Harnessing Max Plank's concept of *quanta*, Niels Bohr proposed that the electrons occupy specific energy levels.

- Erwin Schrodinger suggested the existence of *energy clouds* as opposed to particulate electrons and explained*electron orbitals*. Electrons are therefore more wavelike. He also **did** talk about a cat, but it is beyond our scope.

- James Chadwick, a student of Ernest Rutherford discovered the neutron. It has no charge (is neutral) and resides in the nucleus with the proton. With the discovery of the neutron **isotopy** came to be and so did the concepts **atomic** and **mass numbers**.

- The standard model is a lot…of fun.

- The fermions, bosons and a host of particles make up the standard model. Forces are also accounted for by this model of the atom.

MNEMONICS

Learning stuff can be hard especially when there's so much of it. That's why at the end of every chapter you'll find a few suggestions to aid memorizing lists and processes so that while you learn and have fun you also retain information that would be useful for exams.

- John Dalton's postulates of the atomic theory:

<p align="center">A   S   N   R   S</p>

A – Atoms: As in "Matter is composed of **Atoms."**

S – Similarities: As in "Atoms of the same element show **Similarities** in all ways but differ from atoms of other elements."

N – Neither: As in "Can **Neither** be created nor destroyed."

S – Smallest: As in "The atom is the **Smallest** unit of matter that can participate in a chemical reaction."

And now there are numerous possibilities for what you choose to be a mnemonic. It could be "All Snowboards Never Raid Stores". Ridiculous right? And now all I can think about is snowboards on two feet with ski masks not robbing some unfortunate Hawaiian man by the beach selling well…snowboards but those same snowboard people robbing banks. But you may like to connect the mnemonic with the subject so it could become; "Atomic Snowboards Never Raid Stores."In this case it is connected to our subject and now I can picture John Dalton, the leader of a gang of snowboards with spiraling spheres about them robbing banks. A third option is, "Atoms Show New Research Sometimes." This approach is more direct and no nonsense. However I would suggest some crazy mnemonics. The crazier they are, the more likely they are to stick to mind.

REVISION QUESTIONS

1. Define an atom according to John Dalton.
2. What were previously thought to be the three fundamental particles of the atom?
3. State the names of the scientists who discovered the following:

- The electron
- The proton
- The nucleus
- The positron
- The neutron
- The muon
- The pion

4. Who discovered the atom?
5. What are the postulates of the atomic theory as stated by John Dalton?
6. Describe in a few words the structure of the atom according to the following scientists:

- Erwin Schrodinger
- J.J Thomson
- Ernest Rutherford
- Niels Bohr

7. What is an electron orbital?
8. Define the atomic and mass numbers of an element.
9. What is isotopy?
10. Based on this brief introduction, what do you suppose the future holds for the atomic theory? Do you believe the standard model is a final stop on the road or do you think there is more of the madness in store? Give reasons for your answer and don't forget to be imaginative.

CHAPTER 2: MORE ON ATOMS
Reactions, Moles and Equations
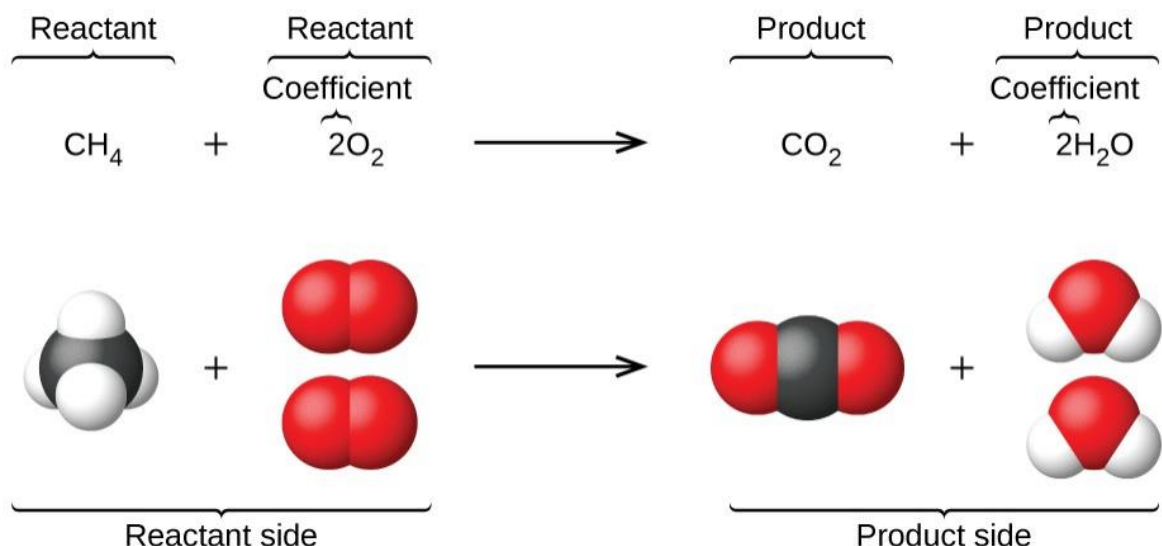
Glad to see you've returned. I am quite sure you must be scratching your head after seeing the topic of this chapter but you needn't fret. The atom is a broad subject indeed but that makes sense right? I mean the atom makes up all matter so it is no wonder that it is so wide in scope.

In the last chapter we very briefly discussed the history of the atom. I say briefly because there is still so much to know if you want to. In this chapter we would be talking about how to represent these atoms and understand them both qualitatively and quantitatively. First off now, we would define some important terms that you would need to understand all we're going to do. Get ready; we would be speaking in the chemistry language shortly.

"An atom is the smallest unit of a substance that can participate in a chemical reaction."

Remember that? I sure hope you do because you'd need it plenty.

"A molecule is a group composed of two or more chemically bonded atoms."

What this means is that when two or more atoms come together they form molecules. The atoms that form a molecule may be of the same or different kinds. For instance if I invited a friend over for arts and crafts and somehow for reasons unknown our jackets became glued together, I alone may just be considered an 'atom' but the both of us together *chemically bonded* (Would explain this later) could be labeled a 'molecule'. If I played around with a single football and got bored quickly and then in a spark of 'genius' decided to glue the football and a basketball together, the single ball could be called an 'atom' while the two balls together (*in chemical bond*) would be a molecule. If I decide that even two balls have little fun potential and add another, maybe a baseball, there would be three separate atoms that chemically bonded together would become a molecule. Now I hope you realize that people and balls do not constitute atoms, but this is just to give you an idea of what atoms and molecules are like. Do not forget the words 'chemical bonds' because in time you will realize that things can be combined in more than one way, and a chemical bond is just one of them.

"Elements are pure chemical substances that cannot be broken down into simpler substances by ordinary chemical means."

Okay, that's a mouthful. Let's break it down.
Atoms when chemically combined make up molecules. Atoms of the *same kind* when held together make up elements and these elements cannot be broken down by any old chemical methods because they are pure chemical substances. Hmm… Something's missing here but can't put my finger on it…

"Compounds are substances that are formed when two or more elements are chemically bonded."

And lastly;

"A solution is a homogenous mixture of substances (solutes) in which the constituents (atoms and

molecules) of the substance are dispersed completely in a solvent."

That's it! And now we have a complete picture.

Atoms make up molecules when they are chemically bonded together. Atoms of the *same kind* make up elements and elements make up compounds via chemical bonds. Solutions contain *solutes* which are composed of atoms and molecules that are uniformly dispersed in a *solvent.* Neat right?
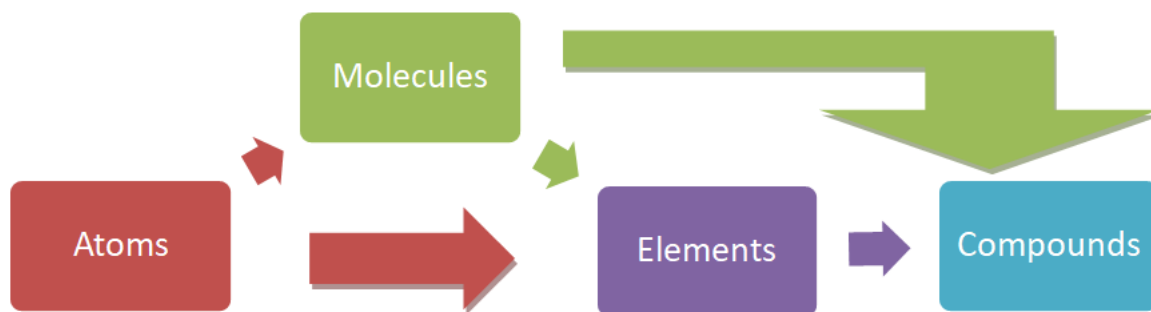

Figure 2-1 (In Shakespeare's voice) "Atoms beget molecules, solutions and elements and molecules also beget solutions, elements and compounds and elements beget compounds."

Now that we have known what they are, how about finding some examples? Clearly human beings and balls aren't atoms even though they are made of them. We've been talking about them and I've seldom given an example but that's because it's easy to get carried away by names and not know exactly what you're talking about.

What are Atoms and Elements really?

Usually we begin our discussions with the atom, but this time we would be giving instances of the elements and it is only in that way that we would come to understand the atom.

The table below is the **Periodic Table**.

Periodic Table of the Elements

Figure 2-2 The Periodic Table

It is a table that shows all known elements discovered as well as their atomic and mass numbers. It would be covered in detail later but for now our focus lies in understanding what those little boxes with the letters in them are. Each little box houses an **element.** The elements are shown by those little letters. The **H** in the top most left up there is the element **hydrogen** while the little red box below it labeled **Li** is lithium and so on. Elements are all around us so don't let this weird little diagram confuse you. For instance if you look towards the upper right, in the third box to the right located at the second row, you find an **O**. Know what that O stands for? It stands for **Oxygen**. And I'm sure you probably already know that oxygen is the stuff that keeps us alive, the gas we breathe in through our noses and into our lungs and it is **all around us.** It has to be, else we may all be dead. So now as a mini assignment can you name at least ten elements? It's okay to look at the table because you only just understand the concept.

How would this help you understand an atom? We're getting there.

Atoms are the smallest unit of a substance that can take part in a chemical reaction. Elements can take part in chemical reactions. The smallest unit of an element can be represented by a single letter such as **O** for **oxygen** therefore an atom of oxygen is 'O'. Isn't that simple enough? What then is an atom of carbon? If you don't know what carbon is just look up at the table. I'll wait.

I'm no psychic but I can just tell you got that right. Now if you are asked what the symbol of an atom of carbon looks like you can just write down 'C' and look like a boss while showing off your John Dalton pose (refer to fig. 2, Chapter 1). Could you also say what the symbols for the atoms **hydrogen** and **oxygen** are too?

One plus one equals Molecules

That isn't exactly true but it's just a reminder that chemistry isn't difficult when you understand. In fact it is as easy as 1 + 1. Now that we know what atoms are, what are molecules? What would a molecule of oxygen look like for instance? Let's take a look at that.

$$O - Atom$$
$$O + O \rightarrow O_2 \text{ (Molecule)} \dots \textbf{(1)}$$

And magic! Just like a simple 1 + 1, your single oxygen atoms have become a molecule of oxygen, meaning 2 atoms. This is getting exciting. What else can we play with? Let's try hydrogen.

$$H - Atom$$
$$H + H \rightarrow H_2 \text{ (Molecule)} \dots \textbf{(2)}$$

Just wonderful. I am feeling a little 'mad sciency'. Why don't we go all Frankenstein and combine them? (The atoms I mean).

$$H + O \rightarrow H_2O \text{ (Molecule)} \dots \textbf{(3)}$$

Believe it or not, that little H_2O right there is a molecule of water but don't bother looking for it your bathtub because you won't find it. On the tip of a needle alone there are millions of molecules so imagine how many molecules could fill your bathtub…or don't imagine so you don't get a headache.

As much as we feel some mad science vibes here, we can't go about doing whatever we like. Nature is governed by rules that only the Creator can break and so we can't combine atoms and elements all willy-nilly. The rules of combination will soon be dealt with and you'll see why.

No compound troubles with Compounds

We already know that when elements are chemically bonded they make compounds. You have even come across one of these compounds even though you may not realize it. Remember when we said that only atoms of the *same kind* can form elements? We emphasized the words 'same kind' for a reason. You see, when elements come together they form compounds but these elements must be of different kinds (meaning they must also possess atoms of different kinds) and when

they do, they form compounds. An example of these compounds is water or as you now know, H_2O. Can you tell why water is a compound? I'll wait.

Water is a compound because it contains two elements: Hydrogen (H) and oxygen (O). Another example of a compound is carbondioxide(the air we breathe out of our lungs contains this) formed from the chemical combination of elements carbon (C) and oxygen (O).

$$C - Atom$$
$$O - Atom$$
$$C + O \rightarrow CO_2 \text{ (compound molecule)}....\textbf{(4)}$$

Just like an element, a compound can be a molecule.

You may have noticed the numeral subscripts beside some of the elements, like H_2O and CO_2. This shows the *fixed ratio* of the combination as a result of their chemical bonds. We would revisit that in another section.

Chemical Equations

Congratulations! Don't look so surprised. You move quickly! Before coming to this section you've already known what a chemical equation is. I'll just refresh your memory.

"A chemical equation is a written representation of a chemical reaction."

If you understood that, you would realize that all the equations we have written are *chemical equations.* They show you what and what form what and are extensively used by chemists every day. Chemical equations represent chemical reactions. So what are chemical reactions?

"A chemical reaction is a process that involves the combination of one or more substances to yield one or more resultant substances."

What this implies is that when the oxygen atoms combined, they yielded the oxygen molecule in a chemical reaction and when carbon and oxygen combined they were converted into carbondioxide in a chemical reaction.

With all this talk of elements and compounds, it is easy to get the two mixed up. We certainly do not want that because that could get us very confused. In the table below, the **differences between elements and compounds** are broken down. Refer to it whenever you need to.

Element	Compound
1. An element is made of only one type of atom.	Compounds are composed of different atoms of different elements in chemical combination.
2. Elements cannot be broken down using chemical means or methods.	Compounds can be broken down into simpler compositions or substances.
3. There are only a fixed number of known elements in existence, only about 117.	Compounds are almost limitless, as several chemical combinations of elements are possible.
4. Elements are represented using symbols such as 'O'.	Chemical formulas represent compounds as formulas are a combination of the symbols (the elements), such as CO_2.

Table 2.1 Differences between elements and compounds

Achieve balance with chemical equations

Now that we know what chemical equations are and can differentiate between elements and compounds, the next crucial step is learning how to balance a chemical equation. Just like a children's see-saw chemical equations can be balanced and should be or else something (or someone) may fall off.

Figure 2-3 This is what an unbalanced chemical equation appears like.

Let's revisit equation **(3)** showing the formation of a water molecule one more time.

$$H + O \rightarrow H_2O$$

Look carefully at that equation? What can you observe? I'll wait.

Indeed. Something is definitely wrong. Here we can find **one** hydrogen atom and **one** oxygen atom on the left side of the equation (before the arrow) but on the right side after the arrow we see **one** oxygen atom and then **two** hydrogen atoms! That isn't right. It's like saying 1 + 1 = 3; just doesn't happen. We've got to make this right; we've got to **balance** the equation.

$$2H_2 + O_2 \rightarrow 2H_2O\ldots\textbf{(5)}$$

What do you see now? We have added another hydrogen to the one before the arrow on the left hand side of the equation (The little '2' subscript) added a '2' before the hydrogen molecule. That 'bigger 2' represents a quantity of measurement known as the *mole* and the H_2 shows that there are two atoms of hydrogen, corresponding to one mole of hydrogen. The '2' before hydrogen shows that there are 2 of the H_2 molecule present, meaning 2 moles.

You must be wondering about the subscripts that seemed to appear out of nowhere. Those are there because hydrogen and oxygen are *diatomic.* What this means is that in their most stable form oxygen and hydrogen each exist as 2 atoms making a molecule. They cannot exist as single atoms for very long because those are *unstable*. All the other elements of the periodic table have their own stable states. Some are *triatomic* (show stability with a molecule of three atoms) and others are even monoatomic (single atom). This would be discussed later at length.

$$H - \text{Atom}$$
$$H_2 - \text{Molecule (diatomic)}$$
$$H_2 - \text{One mole of hydrogen}$$
$$2H_2 - \text{Two moles of hydrogen}$$
$$2H_2 - \text{Four atoms of hydrogen (i.e. first 2} \times \text{second 2), two moles of hydrogen}$$

In the final equation, we now find **four** hydrogen atoms and **two** oxygen atoms while on the right hand side we find the same number of elements now combined into the product water(the big '2' in front of hydrogen also means '2' for oxygen). The equation can now be said to be balanced. One final thing is missing though, and that is the absence of the *states* of the elements. What do you think this means? It means that we've got to know if the elements represented are solid, liquid or gas.

$$2H_{2\,(g)} + O_{2(g)} \rightarrow 2H_2O_{\,(l)}$$

The little (g) represents the term 'gas' showing that hydrogen and oxygen are both in the gaseous states in this reaction while (l) represents liquid, showing that the water formed shown on the right had side of the equation is in the liquid state.

It takes a lot of effort talking about 'right sides' and 'left sides' of the equation. I think we should make it easier on ourselves by calling them **reactants** and **products** of the reaction.

"Reactants are substances that undergo a chemical reaction to give products. They are shown on the left side of the equation."

While…

"Products are formed when reactants undergo a chemical reaction. They are found on the right side of the equation."

So in the above example, hydrogen and oxygen are the reactants, while water is the product formed. Now that we know what reactants and products are, the definition of a chemical reaction would change only so slightly;

*A chemical reaction is a process that involves the conversion of one or more **reactants** to yield one or more **products**."*

Now why not return to the equation for the formation of CO_2 and try to fix it?

Avogadro and his moles (Not the animal kind)

Have a quick glance at the equation below:

$$2H_{2\ (g)} + 2O_{2\ (g)} \rightarrow 2H_2O_{2\ (l)} \ldots \textbf{(7)}$$
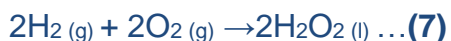
What smells fishy? It isn't moles; I don't think they smell like fish. You have seen these bigger numbers standing before the elements before. While we explained how

they balanced the equation, we did not explain what they were in detail. These numbers are *moles.* However to truly understand the mole we must go first to the work space of an impressive scientist named Amedeo Avogadro. Walk with me. Amadeo Avogadro was an Italian scientist who while studying gases formulated the law known as Avogadro's law. This law states that gases of equal volume at the same temperature and pressure contain the same number of molecules. It is an essential law in chemistry and has given rise to a multitude of important findings. While he busies himself with measuring gas temperature, pressure and volume, let's revisit the statement of this law and keep it in mind.

"Avogadro's law states that equal volumes of all gases at the same temperature and pressure contain the same number of entities or units."

This number known as **Avogadro's number** is **$6.02214076 \times 10^{23}$** and the *entities* or *units* mentioned could be atoms, molecules, electrons or ions. (You would soon come to know what ions are, so don't worry).
And this now leads to the definition of a mole.

"A mole is defined as the mass of a substance that contains 6.02×10^{23} units (molecules, atoms, electrons or ions) of that substance."

This definition looks pretty on paper but it can be very difficult to work with experimentally speaking. While I can say that the same volume of oxygen and hydrogen have the same number of entities, it would be difficult to find a central value for this measurement as the atomic weight of oxygen differs from that of hydrogen. Scientists therefore agreed on a standard, and that standard is 12 grams of the carbon-12 isotope.
Don't fret, I'll explain. You may remember that we defined isotopy in chapter one. I'll juggle your memory.

"Isotopy is the existence of atoms that have the same atomic numbers but different molecular masses (mass numbers) due to a difference in the number of neutrons."

Carbon has three isotopes: carbon-12, carbon-13 and carbon-14. The numbers 12, 13 and 14 are the mass numbers of the elements. If you remember correctly…

"Mass number is the number of protons and neutrons in the nucleus of an atom."

The reason why the mass numbers differ is that they all have different neutron numbers. The atomic number for carbon is 6. Carbon-12 therefore has 6 neutrons and carbon-13 has 7 neutrons. How many neutrons does the carbon-14 isotope possess? Remember that:

Mass number = Number of protons + Number of neutrons

12 grams of the carbon-12 isotope has been chosen as the mole standard, altering our definition of the mole slightly to:

"The mole is the amount of a substance that contains as many elementary particles or units as they are in 12 grams of the carbon-12 isotope."

If this seems too complicated to get your head around, an easier way to remember the mole is to know that the mass number (or atomic mass) in grams of an element is equivalent to 1 mole of that element. For instance;

Atomic mass of oxygen – 16

Atomic mass of oxygen in grams – 16 grams

1 mole of oxygen (O_2) = 16 grams

2 moles of oxygen ($2O_2$) = 32 grams (16 grams × 2)

We therefore see that 16 grams (1 mole) of oxygen contains as many elementary particles as they are in 12 grams of the Carbon-12 isotope.

In the case of compounds such as H_2O;

Atomic mass of hydrogen (H) = 1

Atomic mass of oxygen (O) = 16

Relative molecular mass of H_2O – 1(atomic number of H) × 2(number of H atoms) + 16 (atomic mass of O) = 18 grams

1 mole of water (H_2O) = 18 grams

2 moles of water ($2H_2O$) = 36 grams (18 grams × 2)

When analyzing equations we speak of moles so as to balance them just like we did earlier. Now, tell me how many grams make two moles of hydrogen?

Finding solutions to the mole problem

Solutions form when substances combine. Solutions contain solutes. When two solutions are mixed, the number of moles of solute in one solution exists in a ratio to the number of moles of solute in the other solution. This ratio of solute in solution relative to a specific volume of the solution is referred to as its **concentration**. Concentration is measured in **moles per cubic decimeter** or **moldm^{-3}.** What this simply means is that you find an estimate of the number of moles of the solute present in each decimeter cube of the solution. 1 dm^{-3} is equal to 1000 cm^3 which is equivalent to 1 litre. It is important that you note the following formula to aid calculations in this scope.

$$\text{Concentration (moldm}^{-3}\text{)} = \frac{\text{amount of solute (mol)}}{\text{Volume (dm}^3\text{)}} \text{...(8)}$$

"A solute is a substance that is dissolved in a solvent to form a solution."

"A solvent is a substance that dissolves a solute to form a solution."

Let's play around with some problems so you familiarize yourself with the concepts.

1. Write down the masses occupied by 6.02×10^{23} atoms of the following elements:

    a. Ca

    b. Cu

    c. N_2

    d. O

    e. H_2

Solution

a. 1 mole of a substance contains 6.02×10^{23} elementary entities.

   1 mole of an element is equivalent to the atomic number of the element in grams.

   The mass occupied by 6.02×10^{23} elementary entities of Ca is therefore 40 grams (or 40 g)

   *Consult the periodic table to confirm these atomic numbers.

b. 1 mole of a substance contains 6.02×10^{23} elementary entities.

   1 mole of an element is equivalent to the atomic number of the element in grams.

   The mass occupied by 6.02×10^{23} elementary entities of Cu is therefore 63.55 grams (or 63.55g)

c. 1 mole of a substance contains 6.02×10^{23} elementary entities.

   1 mole of an element is equivalent to the atomic number of the element in grams.

   The mass occupied by 6.02×10^{23} elementary entities of N_2 is therefore 28 grams (or 28 g)

   *I imagine you're wondering what's even going on. Perhaps you had checked the periodic table and saw a 14 for nitrogen. This is because 14 is the **atomic number** for nitrogen, meaning the number of protons or electrons in an atom of an element. Nitrogen however shown here is N_2. It is a molecule of nitrogen (in its stable state) with 2 atoms. So we know that we have to add the 14 of the first atom to the 14 of the second atom to deduce the overall atomic number of the molecule.*

$$N + N \rightarrow N_2$$
$$14 + 14 = 28$$

d. 1 mole of a substance contains 6.02×10^{23} elementary entities.

   1 mole of an element is equivalent to the atomic number of the element in grams.

   The mass occupied by 6.02×10^{23} elementary entities of O is therefore 16 grams (or 16g)

e. *Refer to (c.)*

   1 mole of a substance contains 6.02×10^{23} elementary entities.

   1 mole of an element is equivalent to the atomic number of the element in grams.

   The mass occupied by 6.02×10^{23} elementary entities of H_2 is therefore 2 grams (or 2 g)

2. What is the mass of 0.5 moles of CO_2?

   *When faced with questions of this nature, you find the **relative molecular mass** of the compound by adding the masses (atomic masses) of the individual atoms.*

   Solution

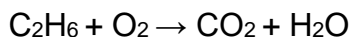 | | C | | O | | O |
   |---|---|---|---|---|---|
   | *Individual masses:* | 12 | + | 16 | + | 16 |
   | *Total mass:* | | | 44 grams | | |

   Since 1 mole of a substance is equivalent to the atomic number of an element or the relative molecular mass of a compound; 1 mole of CO_2 is 44 grams.
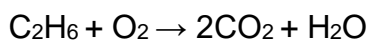
   If   1 mole = 44 grams

   Then   0.5 moles = x

   X = 44 grams × 0.5 moles

   = 22 grams (or 22g)

3. Balance the following equation:

 $$C_2H_6 + O_2 \rightarrow CO_2 + H_2O$$

   Let's begin by looking at each element on both sides of the equation. Begin with C. There are two carbon atoms on the reactant side, but only one on the product side. Let's try to balance this by putting a '2' in front of the C on the product side.

   $$C_2H_6 + O_2 \rightarrow 2CO_2 + H_2O$$

   Now we have two carbon on each side. However, oxygen is now 2 on the reactant side and 5 on the product side (multiply the 2 in front of CO_2 as it includes oxygen by the subscript 2 beside oxygen and add those to the single O

in H_2O.) We see that the equation is still not balanced. This just goes to show that you may require more than one try to balance an equation.

Now let's try something else. Let's begin with H instead. H is 6 on the reactant side so we add 6 in front of H on the product side. This has made the product H now 12 and the reactant H remains 6.

$$C_2H_6 + O_2 \rightarrow CO_2 + 6H_2O$$
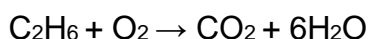
Then we balance O and C. Product O is now (6 + 2) which is 8. We can put a 4 in front of reactant O but the equation won't be balanced. Instead let's put a 4 in front of product C.

$$C_2H_6 + O_2 \rightarrow 4CO_2 + 6H_2O$$
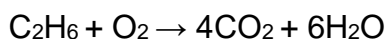
Product O has become 14. We can add a 7 to reactant O to balance O.

$$C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O$$
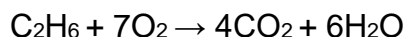
What about C? It is 4 on the product side and 2 on the reactant side. We now add a 2 to C on the reactant side and it becomes balanced.

$$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O$$
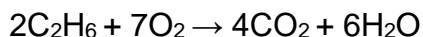
As you can see, H is also balanced on both sides. Take a careful look at the equation. You will notice that all the elements are balanced on both sides.

4. How many moles of calcium chloride ($CaCl_2$) are there in 1 dm^3 of 2.0 $moldm^{-3}$ of solution?

<div align="center">Solution</div>

Applying, the initial equation;

Concentration ($moldm^{-3}$) = <u>amount of solute (mol)</u>
Volume (dm^3)

Volume = 1dm^3
(It is imperative that we convert the volume to dm^3 but in this case we don't have to.)
Concentration = 2.0 $moldm^{-3}$
Amount of solute in moles (also known as number of moles of solute) = X (unknown)
Make X (amount of solute) the subject of the equation;

$$\text{Amount of solute (mol)} = \text{Concentration (moldm}^{-3}) \times \text{Volume (dm}^3)$$
$$X = 2.0 \text{ (moldm}^{-3}) \times 1 \text{ (dm}^3)$$
$$X = 2 \text{ moles.}$$

*NOTE: Many students of chemistry, mathematics and the other sciences have adopted a bad habit of neglecting standard units in their calculations such as **kg, g, moldm^{-3} or cm^3.** It is easy to fall into that negligence trap but please don't. I know I did that for a while until I realized my mistake, after which it caused me some good marks and more importantly some good learning. You need to understand that the S.I units are as involved in the calculations as the numbers themselves. For instance, take a look at the equation above:*

$$X = 2.0 \text{ (moldm}^{-3}) \times 1 \text{ (dm}^3)$$

Let's spread this wide a bit;

$$X = 2 \times \frac{\text{moles}}{\text{dm}^3} \times 1 \times \text{dm}^3$$

Now we divide;

$$X = 2 \times \frac{\text{moles}}{\text{dm}^3} \times 1 \times \text{dm}^3$$

$$X = 2 \times \text{moles} \times 1$$

$$X = 2 \text{ moles.}$$

Isn't that clearer? Don't forget this the next time you solve any equations.

Empirical, Molecular and Structural Formulas

We have come across the term 'relative molecular mass' before. We were trying to calculate the mass of compounds like H_2O by adding the individual masses of the atoms that make up the compound. The relative molecular mass is not only useful in calculating masses but also aids scientists in finding out what the possible formulas of compounds are. In some cases chemists are given a certain material that contains a number of elements but have no idea *in what ratio* these elements are combined or what the arrangement of the atoms in each molecule are. In such cases they carry out experiments to find out the masses of the individual elements and then are faced with the problem of finding out what the formula of that compound to be. Two kinds of formulas are obtained from this analysis. These are the **empirical** and **molecular**

formulas. A formula that can also be obtained is the **structural formula** but this will be thoroughly dealt with later.

"An empirical formula is a formula that shows the simplest ratio of elements that are present in a molecule of a compound but does not show the specific number of atoms in a molecule of the compound or arrangements of the elements in a molecule of that compound."

A bit of a mouthful, but all it really says is that empirical formulas give you suggestions of how much of each element is present in the compound but can't tell you the exact number of atoms in one molecule or in what way they are arranged. For instance with just an empirical formula, how can I tell if 'C' should be before 'O' in CO_2? What if it's the other way around?

"A molecular formula gives the total number of atoms present in each molecule of a compound."

The molecular formula is more exact. It shows the specific number of atoms in one molecule of a compound.

"A Structural formula is a formula that shows how atoms are arranged in a molecule of a compound."

As stated earlier, this would be dealt with later. You would certainly want to stick around because it is literally a beautiful subject.

EXAMPLES

5.6 g of a compound containing carbon, hydrogen and oxygen on combustion gave 7.2g of CO_2 and 4.5 g of H_2O. The relative molecular mass of the compound was found to be 62.

    a) What are the masses of C, H and O are contained in 5.6g of this compound?

b) What are the simplest (empirical) and molecular formulas of the compound?

<div align="center">Solution</div>

a) Let's begin with carbon.
Mass of unknown compound = 5.6g
Mass of CO_2 given off on combustion = 7.2g

Mass of CO_2 relative to mass of compound $= \dfrac{7.2}{5.6} = 1.286g$

Mass of C in $CO_2 = \dfrac{12}{44} = 0.273g$

Percentage of C in compound = Mass of CO_2 relative to mass of compound × Mass of C in CO_2 × 100%
= 1.286 × 0.273 × 100%
= 35.0%

Percentage of C in compound is therefore 35%.
Mass of C in the compound is gotten by the following;

$$35\% = \dfrac{X}{5.6} \times 100\%$$

Where **X** is the mass of C in the compound.
$$196 = 100X$$
$$X = 1.96g$$

The mass of C in the compound is 1.96g.
Now we find the mass of Hydrogen.

Mass of unknown compound = 5.6g
Mass of H_2O produced on combustion = 4.5g

Mass of H_2O relative to mass of compound $= \dfrac{4.5}{5.6} = 0.804g$

Mass of H in $H_2O = \dfrac{2}{18} = 0.111g$

Percentage of H in compound = Mass of H_2O relative to mass of compound × Mass of H in H_2O × 100%
= 0.804 × 0.111 × 100%
= 8.9%

Percentage of H in compound is therefore 8.9%.
Mass of H in the compound is gotten by the following;

$$8.9\% = \dfrac{Y}{5.6} \times 100\%$$

Where **Y** is the mass of H in the compound.
$$49.84 = 100Y$$
$$Y = 0.50g$$

The mass of H in the compound is 0.50g.

We don't need to repeat the entire process for oxygen since we know the percentages occupied by the other two elements. Percentage mass of oxygen is then:
100% - (% mass of C + % mass of H)
= 100% - (35.0% + 8.9%)
= 100% - 43.9%
= 56.1%

To find the mass of oxygen in the compound, we repeat what we've done with the other two:

$$56.1\% = \frac{Z}{5.6} \times 100\%$$

Where **Z** is the mass of O in the compound.

$$314.16 = 100Z$$
$$Z = 3.14g$$

The mass of O in 5.6g of the compound is 3.14g

In order to confirm this, you can add all three masses together and see if the result is 5.6g. When you do, you'll find that it is exactly 5.6g and in that case we are correct.

b) *In order to obtain the empirical formula, we begin by finding out how many moles of the atoms are present in the masses. For instance how many moles of C atoms are there in the 0.96g of carbon in the unknown compound? We can know this by dividing the masses by their respective molar masses (masses occupied by 1 mole).*

C : **H** : **O**

$$\frac{1.96}{12} \quad : \quad \frac{0.50}{1} \quad : \quad \frac{3.14}{16}$$

$$0.163 \quad : \quad 0.500 \quad : \quad 0.196$$

*What we do next, is divide these numbers by the number of **least magnitude** or the **most occurring.** In this case the most occurring is 0.163.*

$$\frac{0.163}{0.163} \quad : \quad \frac{0.500}{0.163} \quad : \quad \frac{0.196}{0.163}$$

$$1 \quad : \quad 3 \quad : \quad 1$$
$$C \quad : \quad H_3 \quad : \quad O$$

The ratio of the constituents is 1:3:1 so the empirical formula becomes **CH_3O.**
*The molecular formula makes use of the **Molecular mass** and the **Empirical Formula Mass.** The empirical formula mass can be gotten in the following way:*

$$CH_3O = 12 + (3 \times 1) + 16$$
$$= 12 + 3 + 16$$
$$= 31g$$

*You then divide the molecular mass given by the empirical formula mass to obtain a special number **n**. The molecular mass in this case is 62.*

$$n = \frac{\text{Molecular Mass}}{\text{Empirical Formula Mass}}$$
$$n = \frac{62}{31}$$
$$n = 2.$$

Finally, we multiply n by the ratios of the empirical formula. The molecular formula thus becomes;

$$(CH_3O)n$$
$$=(CH_3O)\,2$$
$$= C_2H_6O_2$$

This final result is the molecular formula of the compound

- An atom is the smallest unit of a substance that can take part in a chemical reaction.
- A molecule is a group composed of two or more chemically bonded atoms.
- Elements are pure chemical substances that are composed of atoms of the same kind.
- Compounds are composed of two or more chemically bonded elements.
- A solute is a substance that is dissolved in a solvent to form a solution, while a solvent dissolves a solute to form a solution.
- A solution is a homogenous mixture of substances (solutes) in which the constituents (atoms, molecules and ions) of the substance are dispersed completely in a solvent.
- The periodic table consists of all the known elements and their atomic numbers.
- A chemical equation is a written representation of a chemical reaction.
- Reactants are substances that undergo a chemical reaction to give products and are found on the left side of the equation.
- Products are substances formed when reactants undergo a chemical reaction. They are found on the right side of the equation.
- A chemical reaction is a process that involves the conversion of one or more reactants to yield one or more products.
- Elements and compounds show significant differences (check the MNEMONICS section of this chapter).
- An unbalanced chemical equation is not a pretty sight to a chemist.
- Avogadro's law states that equal volumes of all gases at the same temperature and pressure contain the same number of molecules.
- A mole is an amount of a substance that contains as many elementary entities or units as they are in 12g of the carbon-12 isotope.
- An empirical formula shows the simplest ratio of elements present in a molecule of a compound.
- A molecular formula shows the total number of atoms present in a molecule of a compound.

- The structural formula of a compound shows the arrangement of the atoms in a molecule of the compound.

MNEMONICS

Here we would be attempting to memorize the differences between elements and compounds.

<div align="center">T   B   N   S   (F)</div>

T – Types: As in "Elements are composed of one **type** of atom, while compounds are not**."**

B – Broken down: As in "Elements cannot be **broken down** into simpler forms but compounds can."

N – Number: As in "They are a fixed **number** of known elements in existence, but the **number** of compounds are almost limitless."

S – Symbols: As in "Elements are represented by **symbols** but compounds are represented by chemical **formulas**."

The 'F' stands for **formulas** and is optional.

Can you think up interesting mnemonics with this? How about; 'Tall Bats Never See (Far)'? or maybe 'Tiny Bosons are Nature's Symbols (and Formulas)' ? That has got something to do with atoms at least. Think up creative mnemonics so you never forget them.

REVISON QUESTIONS

1. Define the following terms:
    a) An atom
    b) A molecule
    c) An element
    d) A compound
    e) A solution
    f) Atomic number
    g) Mass number
    h) Solute
    i) Solvent
    j) A mole

2. Chlorine has two well known isotopes which are chlorine-35 and chlorine-37.
   How many protons, electrons and neutrons does each isotope possess?

3. State four differences between elements and compounds.

4. Balance the equations below:
    a) $CO_2 + H_2O \rightarrow C_6H_{12}O_6 + O_2$
    b) $KClO_3 \rightarrow KClO_4 + KCl$
    c) $Fe_2O_3 + C \rightarrow Fe + CO_2$
    d) $Al + HCl \rightarrow AlCl_3 + H_2$
    e) $FeCl_3 + MgO \rightarrow Fe_2O_3 + MgCl_2$

5. Write down the masses occupied by 6.02×10^{23} atomsof the following elements:
    a) Mg
    b) Na
    c) O
    d) Be
    e) S

6. Write down the masses occupied by 6.02×10^{23} moleculesof the following elements:
    a) F_2
    b) O_2
    c) P_4

7. What are the number of atoms in;
    a) 0.5 moles of H_2O

b) 12g of Mg

c) 2 moles of NaOH

d) 6.5g of Ca

e) 0.1 moles of O_2

8. How many moles of sodium iodide (NaI) are there in 1000cm^3 of 3.0 moldm^{-3} of solution?

9. 6g of an element X with a molecular mass of 40 reactedwith 12g of chlorine to form a chloride.

   a) How many moles of chlorine combined with one mole of X?

   b) What is the simplest formula of the chloride?

10. Is it true that equal volumes of all gases weigh the same? Give reasons for your answer.

CHAPTER 3: CONFIGURATIONS AND CHEMICAL BONDS

Imagine a universe where atoms are rigidly unsociable and never meet other atoms for tea, or to walk their electron pets or dance to Maroon 5 or Korede Bello. How such a bore that would be! There would be no working together so they'll be little development. Structures won't be formed and that dear friend, means you and I won't even be here. Atoms on their own are fascinating building blocks, but in the absence of combining with other atoms they build nothing. All the beautiful things around us have atoms that make them up. The very biological processes we undergo are as a result of the atoms and molecules that make up our bodies. You and I are physical beings and can feel the air, touch random strangers (don't do it, believe me I know), feel pain when we suddenly strike our feet on surfaces, run our fingers through running water and slap that annoying cousin we see every Christmas (also, don't do it). We can do all this because atoms have chosen to be friendly with each other; because they have decided to create **bonds.**
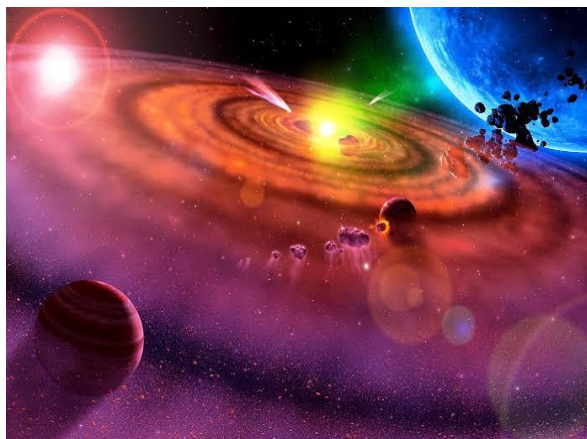

Figure 3-1 Everything is made from atoms because atoms bond.

In fact, they **have** to create bonds. Just like many adults and almost all kids atoms have a hard time sitting still. I can't blame them; I have a hard time sitting still. There's always

so much to do, and even writing this book is an example. The reason for this is that just like how the very point of life for many people is to be mentally, physically, emotionally and financially stable and happy, atoms also want to be stable and happy. Okay, maybe not 'happy' but they want to be stable nonetheless. Not sure what this stability means? Hang on a bit and find out.

The Octet Rule

If there was one thing in the world that could make all your dreams come true and you knew how to get it, wouldn't you go for it? I've got no supernatural powers (unless you count not sleeping) but I'm quite sure you said yes. Also, just on a friendly note, no matter how stressful school and work get, make sure you get some sleep; always. Atoms have figured their key for ultimate stability and it is called the **octet rule.** Atoms here are trying to balance the number of electrons on their shells by getting at least close to 8 electrons on their outermost shells (hence the name 'octet') in imitation of the **noble gasses.**

Noble gasses are found on the farthest column to the right of the periodic table. You can look them up. Elements found there are helium (He), Neon (Ne), argon (Ar), Krypton (Ke), Xenon (Xe), Radon (Rn) and Oganesson (Og). An interesting fact to know is that Oganesson was discovered only in as recently as 2002. That may not seem so recent but many chemistry texts have not included it in this list. I didn't learn about it in school but I'm glad you can.

The noble gases listed above are the popular guys of the periodic table kingdom. Everyone else wants to be them because they are so chill, nothing seems to bother them. The other elements want a taste of that cool. The only to achieve that is to have at least a near octet outer shell. Let's find out how to go about helping the elements get cool with some help from Gilbert N. Lewis. Walk with me again.

Figure 3-2 Gilbert N. Lewis working.

It is the year 1916 and we find the American scientist on his desk writing extensively an article titled: *The Atom and the Molecule*. I sit on a chair and nearly fall to the floor dozing off (Wow. I need to sleep) while you bend over the shoulders of the scientist and find strange diagrams just like the ones below:
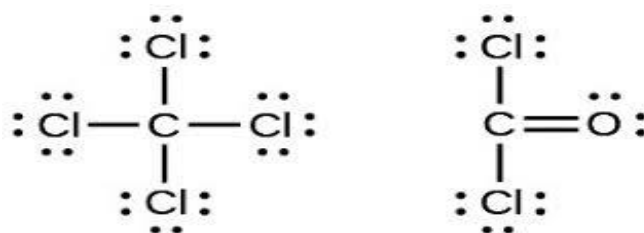

Figure 3-3 A Lewis dot structure.

What could these weird dots and dashes possibly be? The dashes and dots are *valence electrons.*

"Valence electrons are the electrons located on the outermost shell of an atom."

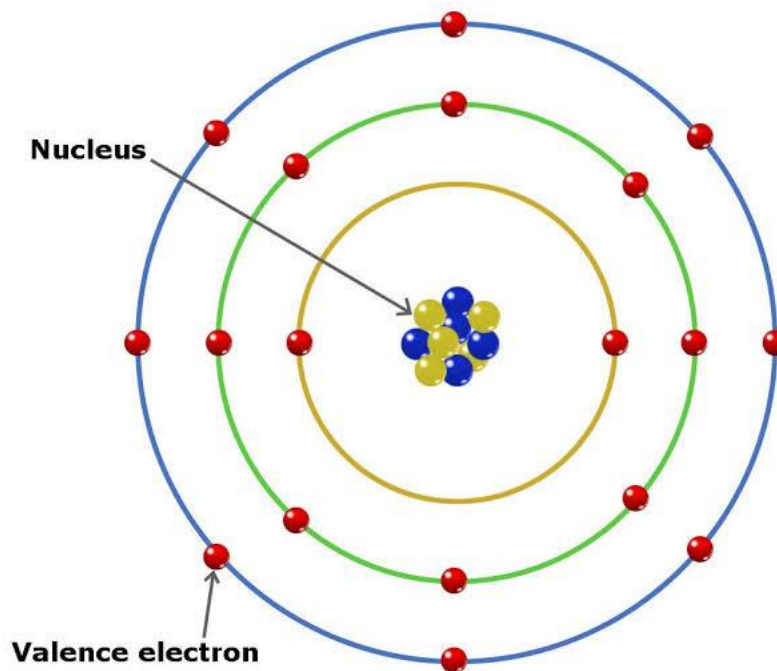Carefully study the diagram below.

Figure 3-4 Atomic structure showing the nucleus and valence electrons.

All those concentric circles you see above are orbitals or *shells* of an atom. Whenever an atom interacts with other atoms, the valence electrons on these *valence shells* are the first to participate in the reaction.

Picture this. Imagine you are seated in a classroom with the rest of your classmates for a chemistry lesson (just a randomly chosen subject) and there is only one door to the classroom located at the back of it. None of you hold on to anything and never do for the duration of that class. You all also roughly weigh the same. If a sentient gigantic vacuum cleaner paid a surprise visit to your class and standing at the door began sucking up all of you, based on the location of the door which students would be the first to be sucked in? The ones seated in front or the ones at the back? I'm guessing you said the ones at the back. If so, congratulations! Here's a cookie.

Just like your classroom, the electrons situated farthest from the nucleus in the middle of the atom would be the ones to participate when other atoms show up to engage the atom.

But wait. There's more. The electrons located at the farthest shell of the atoms are there on account of something known as the **screening effect.** The electrons are negatively charged. The protons in the nucleus are positively charged. Remember when we mentioned that negative and positive charges attract each other? Similar charges on the other hand repel each other. So when more than one electron exists in an atom, all the electrons exhibit what is known as a *screening effect*. This means that they screen each other or in simpler terms refrain from 'touching' each other on account of the fact that

they possess the same charge and as we know, their negative charges should and do repel each other. What this means is that the screening allows for greater distance between them, and naturally some electrons are pushed to the valence shell.

But how do we **know** them? If I were asked to say how many valance electrons oxygen had would I be able to? I just may so now let's get you to do so too.

Deducing the number of valence electrons of atoms

In order to easily visualize how electrons are arranged in an atom and work with atoms, the shells are labeled **K,L,M,N** and it continues. Each shell is given the number **n**, known as the **principal quantum number** where **n** is1, 2, 3 and so on depending on the location of the shell, so that the shell closest to the nucleus is given n = 1 and the second shell is n = 2 and on it goes.

The numbers are important because they can be inputed into the formula **$2n^2$** which helps to show how many electrons are in a particular shell. If your memory is really sharp, I'm quite sure an old friend visited your thoughts, and this image from chapter one crossed your mind:
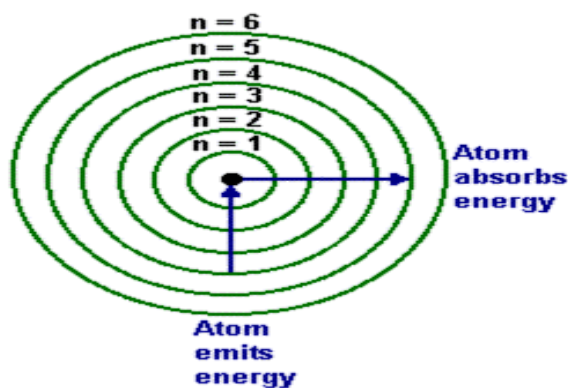

Figure 3-5 Niels Bohr's atomic depiction showing the electron shells.

That's right. The idea of **electronic configuration** which shows how electrons are arranged in atoms is the brain child of our old friend, Niels Bohr. Let's add a little thing in the light of new information.
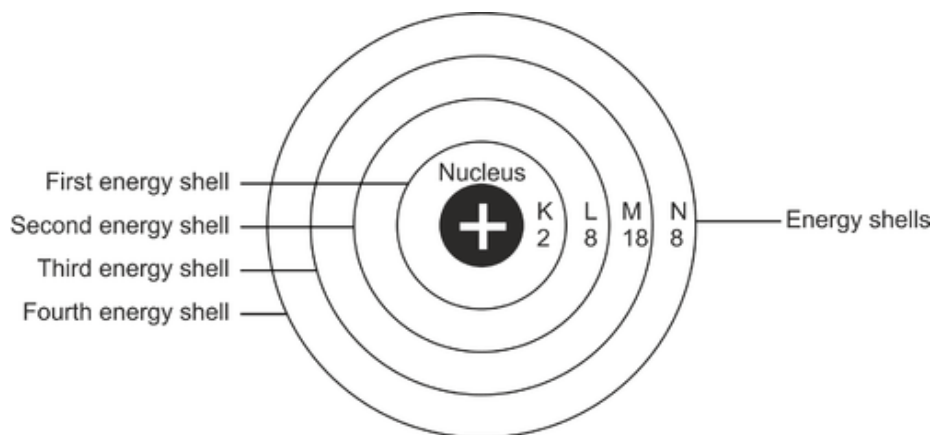
Figure 3-6 The electron shells labeled.

The first shell is the K shell meaning n=1. In order to know how many electrons occupy that shell, we use the equation $2n^2$. When we substitute n for 1 as in;

$$2n^2 = 2 \times (1)^2$$
$$= 2 \text{ electrons.}$$

We therefore now know that the K shell occupies 2 electrons and can only occupy 2 electrons. What about the L shell? n for the L shell is 2 so the number of electrons on the shell are 8. Can you find out how many electrons are on the M and N shells? I'm sure you can. I'll wait.

It's about time for some real world examples or as real as the mysterious atoms can get. Let's try deducing the arrangement of electrons on say, the oxygen atom. Oxygen has an atomic number of 8 and a mass number of 16. Right now our focus is on the atomic number. An atomic number 8 means that the number of protons are 8 but if you have been following carefully, you would remember that atomic number is not just the number of protons, but the number of electrons as well because in a neutral atom the number of electrons are protons are equal. What this implies is that the number of electrons in an oxygen atom are also 8. Let's try arranging these 8 electrons on the shells of our oxygen atom.

We can start with the K shell. We have already established that the K shell has a maximum of 2 electrons, following the $2n^2$ formula and that the L shell has a maximum of 8 electrons. How many shells do you think oxygen has then? How would you arrange the electrons on the shells and how many valence electrons does it have? I'll wait.

Asking where I went to? Oh I took a well-deserved break because teaching is hard. Not that I don't love it of course. I also had a cold drink. You could get yourself one. You look like you need your own well deserved break. Done? Let's begin.

Before the break I had left you with a small problem. Did you find the answer? I'm sure you did. Let's solve it together.

Oxygen has atomic number 8. This means it has 8 protons and also 8 electrons. The maximum number of electrons that can fill a K shell is 2 electrons, while the maximum number capable of filling an L shell is 8 electrons based on the formula $2n^2$. Since 2 + 6 is 8, the number of shells required for the oxygen atom are the first two shells; K and L. As for the arrangement, you might want to get a pencil. Look at the diagram below.
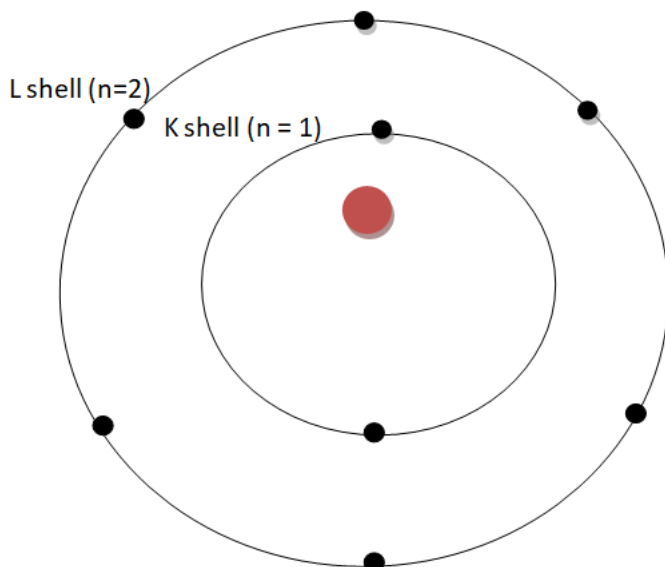
Figure 3-7 Electron shell diagram for oxygen.

As you can see above, the K shell has two electrons while the L shell has 6 electrons. The red oval in the centre represents the nucleus. From the diagram we can see that oxygen's valence shell is the L shell. Therefore oxygen has 6 valence electrons. Try drawing the shell diagram for the element carbon with atomic number 6. How many valence electrons does it have?

Met the shells? Say hello to the sub-shells

I am almost standing on my sit writing about these principal shells (as they are called) we've talked about. This seems to be the first time in a while we've talked about something relatively simple. I mean, all we've got to do is know an element's atomic number and magic! We could know the number of its valence electrons, what it may look like and possibly even what it had for dinner. That's great and suspiciously easy. From what we've known about the atom it loves to play jack-in-the-box and any moment now it'll pop up with a surprise. You probably already guessed it. Yes, the shells aren't the only thing to remember, we will now talk about **sub-shells** and I think you probably don't get why they matter because I didn't get it myself for quite a long time.

They are the subshells of the principal shells denoted by the *spdf* (and so on) notation. While in the principal shells we spoke of the principal quantum number n, with subshells we talk about the **azimuthal quantum number ℓ,** where ℓ is 0,1, 2, 3 and so on depending on the subshell. Hence if the subshell is d, ℓ is 2. This system is analogous to

a desk. There is only one desk, but there are a number of drawers that can be used to store multiple things. In the same way the principal shell K can be further divided into the subshells s, p, d, f and so on depending on how many electrons need to be 'put away' in this subshell. The maximum number of electrons that can be found in a subshell can be gotten by the formula;

$$2(2\ell + 1)$$

Let's summarize this briefly so your mind doesn't become as cluttered as my desk. There are a number of **principal shells** denoted by **K, L, M, N** and so on. These shells show how electrons are arranged in the atom. This arrangement is obtained by harnessing the equation $2n^2$ where **n** is the **principal quantum number** represented by 1, 2, 3, and on depending on the location of the shell relative to the nucleus. The shells are further divided into **subshells** represented by **s, p, d, f** and on it goes**.** These subshells show how electrons are arranged in them using the **azimuthal quantum number ℓ,** which can be can be 0, 1, 2, 3… depending on the subshell so that for the p subshell it is 1. The maximum number of electrons that can occupy a subshell is calculated using the formula **2(ℓ + 1).**

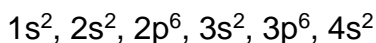## Writing the electronic configuration

We have talked about drawing shells. That seemed nice but could you imagine having to draw that for an atom with atomic number 118? How wide would your paper have to be? This is no joke though, 118 is the atomic number for organesson, the new addition to the periodic family. In order to be merciful to us, not just because it'll take a good deal of space (and time) to draw such a structure but because not all of us are gifted in drawing just about anything, Niels Bohr and other scientists introduced a more terrible artist friendly way to represent the arrangement of electrons in orbitals.

For example, we can talk about **3d.** Not the viewing option 3D but the electronic configuration 3d. What this means is that the electron(s) here is/are on the third principal shell represented by the '3' and the d subshell. If my missing electron is on 4s? What does this mean? I'll wait.

Yes, that means it's on the N principal shell (the 4th principal shell) and the s subshell. If I wanted to represent more than a few electrons but wanted to show all the electrons of one atom, then I'll have to put them all together. For example if you are asked to write the electronic configuration of an atom of chlorine (Cl) with atomic number 17, you would need to put all those shells together. The atomic number of chlorine would then become:

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^5$$
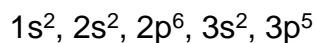
If you add up all those electrons shown by the superscripts you would get 17, the atomic number of chlorine. Following the formula $2(2\ell + 1)$, you would find that the maximum number of electrons in the s subshell is 2 and in the p is 6. Follow this, and you'll be sure to get it right. Let's try another example for good measure. Let's try writing the electronic configuration for calcium (Ca) with atomic number 20.

$$1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 4s^2$$

Try writing the configurations for magnesium (Mg) and Potassium (K) and get a feel for how fun writing them can be.

Laws that aid electron orbital assignment

Chemistry isn't a subject for crazy people…relatively speaking. It's a field that follows rules and this is because the central subject of our studies is one that is dependent on rules as well. When atoms perplex us, it isn't because they are anarchistic, but it's mostly because we just don't understand their rules. However there are some rules we understand and that's because brilliant men and women have learnt them. Some of these rules are the Pauli exclusion principle, Hund's rule and the Aufbau principle and they aid us in knowing the right way to assign electrons to orbitals.

Pauli's Exclusion Principle

Wolfgang Pauli won the 1945 Nobel prizefor the formulation of the **Pauli's exclusion principle** which he formulated in the year 1925. The law states that no two electrons can have the same four quantum numbers. In school I had prided myself on memorizing this law but I never quite knew what it meant. I realize now that it was a waste of time cramming up impressive words. It's better understanding them, so let's understand.

"Pauli's Exclusion Principle states that no two electrons can have the same four quantum numbers."

What this simply implies is that all electrons are unique and as such cannot have the same quantum numbers or occupy the same positions. Examples of these 'quantum numbers' are the principal quantum number and azimuthal quantum number which if you are keen I'm quite sure that you have noticed that the law mentioned **four** quantum

numbers, whereas we have only discussed those two (n and ℓ). They are actually more than two quantum numbers, the others being the **magnetic quantum number** (m$_\ell$) and the **electron spin quantum number (m$_s$)** but those are not as relevant for our present scope but will be dealt with later.

According to Pauli's law, only two electrons can occupy the same orbital, and if two electrons exist in that orbital they must be of opposite **spins.** Spins are a form of angular momentum of an electron. At present, just think of them as 'arrangements' of electrons where each electron is like an arrow pointing in a particular direction. Pauli's principle shows that no two of these 'arrows' could have the same spin (point in the same direction) in the same orbital.
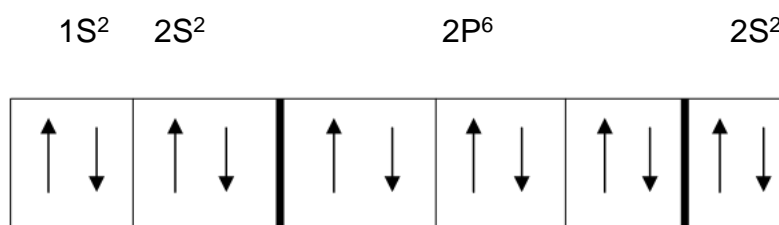
$$1S^2 \quad 2S^2 \qquad\qquad 2P^6 \qquad\qquad 2S^2$$

Figure 3-8 Atomic number of Mg represented by a spin diagram

Each of the boxes above represents an orbital and the number and letter units above are shells. In each orbital you can see that Pauli's principle is obeyed.

Hund's Rule

Friedrich Hund stated this rule in 1925, which concerns how orbitals are filled. Whenever electrons occupy orbitals, they do so one at a time before filling up the shells. I'll explain.

"Hund's rule states that in filling orbitals, electrons do so singly first before occupying the orbitals in pairs."

What this means is that even when a pair of electrons are needed in an orbital, they fill the orbital singly before doing so doubly. The atomic number for oxygen is 8. Its electronic configuration is therefore 1s^2, 2s^2, 2p^4. When asked to show its spin diagram you may give the diagram below:

$1s^2$ $2s^2$ $2p^4$
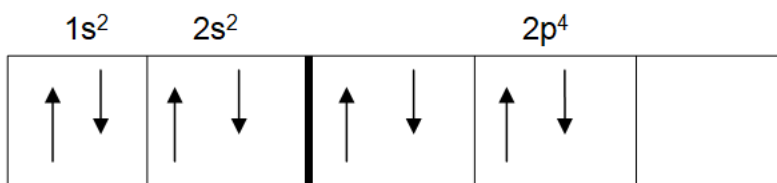
This may seem right to you, but it breaks Hund's law. This is because the third p orbital is empty. It was meant to be filled first before starting again with the first p orbital. If done correctly, the spin diagram of oxygen should look like the one below.
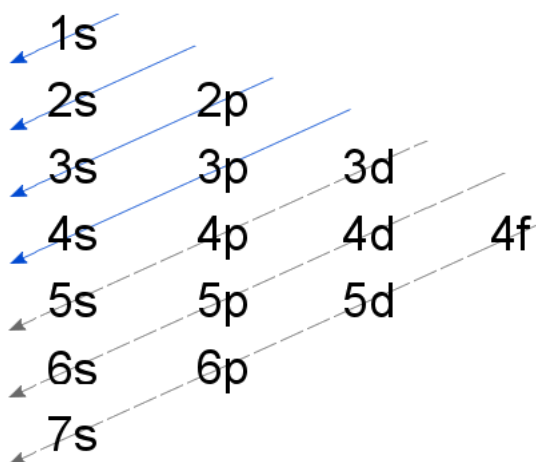

$1s^2$ $2s^2$ $2p^4$
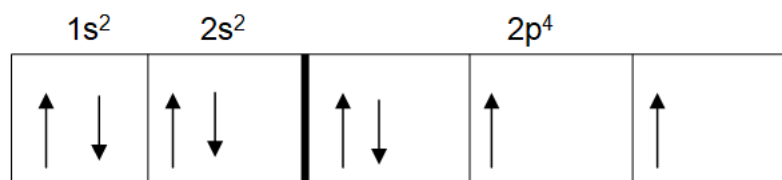
This obeys Hund's rule.

In order to show what orbital has what electrons, it is helpful to divide the three orbitals of the p subshell into **x, y** and **z.** The first p orbital in the above can then be $2px^2$, the second $2py^1$ and the third $2pz^1$. All still amount to 4 electrons when added together.

$1s^2$ $2s^2$ $2px^2$ $2py^1$ $2pz^1$
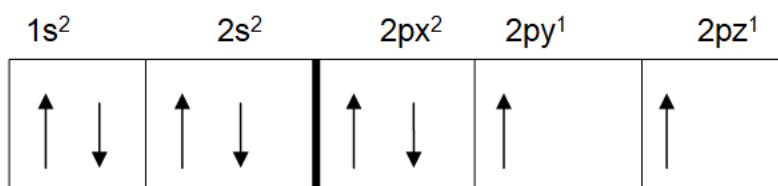
The Aufbau Principle

The word aufbau stems from a German word 'aufbauprinzip' which is 'building up principle'. The principle explains that orbitals can only be filled from the ground state of an atom up. This means that electrons occupy orbitals of lower energies first before moving on to occupy orbitals of higer energy. In the diagram above we see that the

lowest energy orbital is 1s, followed by 2s and then 2p, then 3s and so on. The arrows point from higher to lower energy orbitals. When faced with the problem of writing the configurations of atoms with large atomic numbers, resort to this image for guidance. The image above can be arranged linearly as;

1s, 2s, 2p, 3s, 3p, 4s, 3d, 4p, 5s, 4d, 5p, 6s, 4f, 5d, 6p, 7s and so on.

"The Aufbau principle states that electrons occupy orbitals starting from those with the lowest energies to those with the highest energies."

Now that we know what valence electrons are, shells and electronic configurations are, let's move on in our journey to deciphering those puzzling dots and dashes of Mr. Lewis and in so doing come to understand chemical bonds.

I can tell you're exhausted. All this new knowledge came in like a rush.I t's a good time to set the book down and get a cold drink; fruity flavored if you like and maybe a snack or two. When you return we would be tackling chemical bonds.

Atoms unite! (in chemical bonds)

Wow. We seemed to have left Mr. Lewis by himself so long. Sure hope he isn't angry but then again he probably has been too preoccupied to care. No problem though. We would get along fine.

:C̈l:
|
:C̈l—C—C̈l: :C̈l:
| |
:C̈l: C=Ö:
                |
                :C̈l:
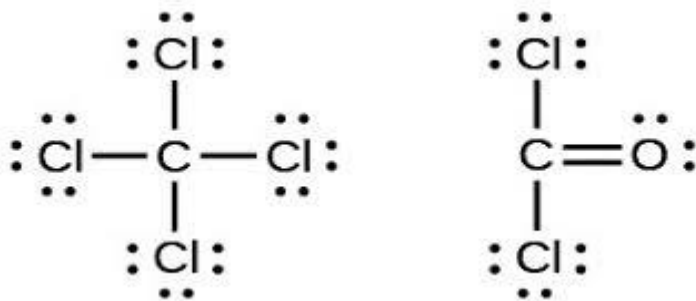
Remember this image? There are the dots and dashes that led us into all that talk about electronic configurations. We should be glad we went through those because they are going to come in handy. The dots and dashes shown in the picture above represent electrons but not just any electrons in the atom. They represent valence electrons which you remember are the electrons on the outermost shell of the atom otherwise known as the valence shell.

When atoms interact, their valence electrons take over and are sometimes given away or accepted. When atoms give their valence electrons away in order to obtain a stable or octet configuration, the type of bond formed by the participant atoms is known as an **electrovalent or ionic bond.**

"An electrovalent or ionic bond is a type of chemical bond formed between atoms in which one atom loses an electron to form a positively charged ion (a cation) and another atom gains the electron to form a negatively charged ion (an anion)."

Remember when we spoke of an **ion** and said we'll revisit it at another time? Now is just that time. When electrovalent bonds are formed the valence electrons are transferred from one atom to the next. Prior to this transfer, both atoms are both relatively neutral. When the atoms interact and form this bond, they change. By giving away an electron one atom changes because the number of electrons have reduced and the number of protons are higher than those of electrons, meaning it is

now less negatively charged than before and hence more positively charged. The atom that receives the electron however now has an increased number of electrons, more so than the number of protons and so is more negatively charged than before. When an atom loses an electron it is no longer neutral and becomes an ion. This ion is more positive than before and so we call it a **cation.** As for the atom that received the electron, it is also no longer neutral and so is an ion. Since this ion has received an electron and become more negative than before, it is now an **anion.**

"*An ion is an electrically charged atom or molecule formed by the loss or gain of an electron.*"

"*A cation is a positively charged ion.*"

"*An anion is a negatively charged ion.*"

By a transfer of electrons hence, electrovalent or ionic bonds are formed. A good example of a compound formed via ionic combination is sodium chloride (NaCl) which you know more familiarly as table salt.

Sodium (Na) has the atomic number 11 while chlorine (Cl) has atomic number 17. The principal shells of Na using the form K,L,M,N can be written as 2,8,1 where there are 2 atoms in the K shell, 4 in the L shell and so on.

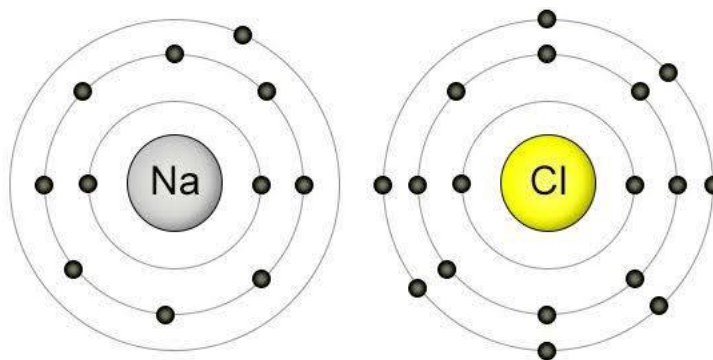For Cl with atomic number 17, its configuration is 2,8,7.

Figure 3-9 Na and Cl dot structures

If you observe, Na needs to lose its 1 electron hanging on the outermost shell in order to achieve an octet configuration. Cl on the other hand needs 1 electron to achieve its own octet configuration. Na is therefore generous and gives its electron away and everyone is happy. An octet configuration simply means that just like the noble gasses, there are now 8 valence electrons on the valence shell of the atom, hence "octet".

When Na gives away its electron, it has a net positive charge as explained earlier. Being more positively charged, it becomes a cation. Cl, in accepting the electron from Na now has a net negative charge. The two bond and tasty food is born thanks to the salt formed.

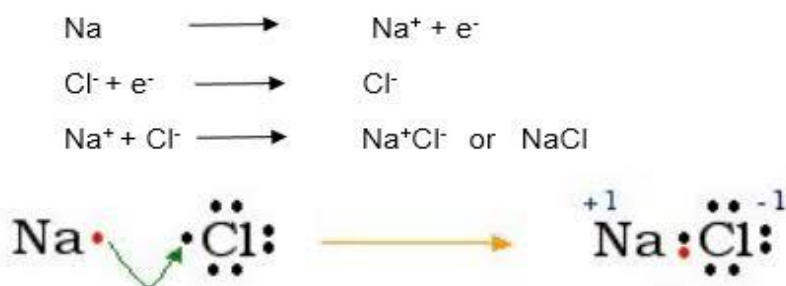This process can be represented by a **Lewis dot structure**.

Figure 3-10

The above is a concise representation of the process. The first equation shows Na losing an electron (e^-) to become a cation, while the second shows Cl gaining an electron to become an anion. The final equation shows the entire process. This is an example of how to write an **ionic equation.** We would write way more of this kind of equation as we move along.

Covalent Bonds

A second type of bond is not concerned with transferring electrons, but has a more 'altruistic' approach. This bond is formed when electrons are shared between participating atoms.

"Covalent bonds are formed when atoms involved in a reaction share pairs of electrons."

Three types of this kind of bonds exist; **single covalent bonds, double covalent bonds and triple covalent bonds.**

The **single covalent bond** occurs when a single pair of electrons is shared by the participating atoms. An example is the bond formed in the formation of the chlorine molecule Cl_2.

:Cl· + ·Cl: ⟶ :Cl:Cl:

chlorine
atoms
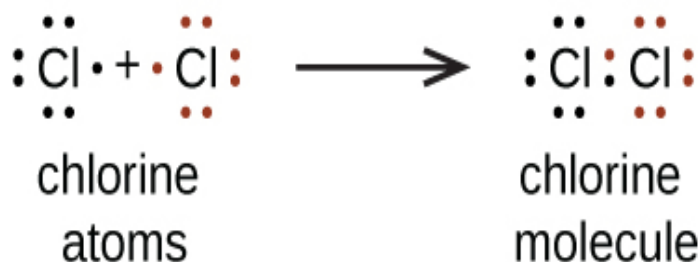
chlorine
molecule

The chlorine atoms require an atom each to complete their octet configuration. In sharing a single pair of electrons, they achieve this and become stable.

The **double covalent bond** is formed between atoms that share two pairs of electrons. For instance the bond found in a methane molecule (CH_4) when C and H combine is a double covalent bond.

H· ·C· ·H ⟶ H:C:H   H–C–H

methane
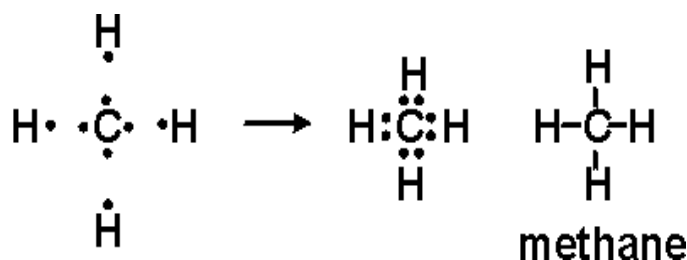
Each molecule of H contributes one electron to share with the C. All four valence electrons of the H taken together is equal to four electron pairs combining with the four pairs of valence electrons of the C making the bond formed a double covalent bond.

The last type of covalent bond we would talk about is the **triple covalent bond**. I'm sure you can already deduce what its definition is, but I'll put it down anyway. This bond is formed when three pairs of electrons are shared by participating atoms in bond formation. Nitrogen gas (N_2) is formed in this way.

:N::N:

:N≡N:

As you can see, three pairs of electrons are shared by the nitrogen atoms. You may also notice that aside from dots, dashes are also used. As shown above dashes

could be used as a substitute for dots, where each dash corresponds to two dots or two electrons.

Properties of electrovalent compounds

The distinctness of an ionic compound doesn't cease when it is formed. The way an electrovalent compound is bonded plays a large part in the characteristics it exhibits. The following features are found in compounds formed from an ionic or electrovalent bond.

1. **Electrovalent compounds are hard:** The ordered arrangement of ions in a crystal lattice and strong attraction between these oppositely charged ions has made the structure of an ionic compound well defined and hard. An example is in table salt (NaCl) which has such crystalline appearance and cannot be distorted so much as to alter its shape.

2. **In the solid state, they are poor conductors of electricity:** This however changes when they are dissolved in solution and their ions are free to move about. NaCl for example can be a great conductor of electricity. You will find out how in the chapter on electrolysis.

3. **They have high melting and boiling points:** In simple terms, boiling point is just an indication of what temperature or how quickly something boils when it is introduced to heat. It is the temperature at which something changes from liquid to gas. Melting point is the temperature at which something melts away when introduced to heat, changing from solid to liquid. Pure water has a boiling point of 100°C. This means that at a 100 degrees celsius, pure water boils and turns to vapour (which is gaseous) as opposed to helium (He) which has a boiling point of just -268.9 °! Unlike He, electrovalent compounds have high boiling points and melting points too. The reason for this is that the ionic bonds formed between the oppositely charged ions are so strong that it would take considerable force to dissociate them and alter their states.

4. **Ionic compounds are readily soluble in water:** When electrovalent compounds come into contact with water, they dissociate into ions as the water molecules are attached to them. For this reason they dissolve in water.
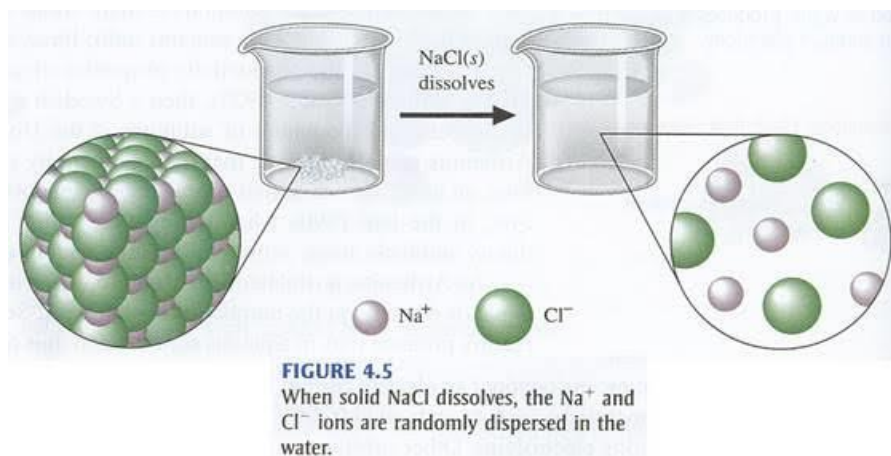
FIGURE 4.5
When solid NaCl dissolves, the Na$^+$ and Cl$^-$ ions are randomly dispersed in the water.

Figure 3-11

Properties of covalent compounds

Irrespective of the type, all covalent compounds share a number of features. These are shown below.

1. **Covalent compounds are usually not hard:** The electrically neutral structure of covalent compounds in the absence of strong electrostatic attraction make them less hard than their electrovalent counterparts. These compounds are usually liquids and solids on account of this. If solids, they can easily be deformed because they are held together by weak intermolecular bonds.

2. **They do not conduct electricity:** In order for a substance to conduct electricity, there must be free charged particles available. Ionic compounds are able to conduct electricity because they produce these particles on dissociation. This cannot be said for covalent compounds, hence they do not conduct. A few exceptions however occur in the right conditions. Hydroiodic acid (HI) and hydrochloric acid (HCl) are these exception. The specific reason for this would be discussed in a later chapter.

3. **They have low melting and boiling points:** Having weak intermolecular forces of attraction explains why they have low melting and boiling points. They can be easily broken down by heat, changing their states from solids to liquids and liquids to gasses fairly easily. They are therefore said to be volatile. An everyday example of this volatility can be seen with kerosene. You must have noticed the ease with which it dissipates when left in the open.

4. **Covalent compounds are not soluble in water:** They are soluble in other solvents however. This is because water is a **polar solvent** while covalent substances dissolve in solvents that are **non-polar**such as carbon

tetrachloride (CCl_4) and benzene (C_6H_6).Don't fret as we would fully discuss what those terms mean later.

Associate forces of attraction

Aside from those mentioned above, a number of other bonds exist alongside them. For a long time it was believed that there were two distinct bond types (those already mentioned) but scientists are beginning to see that chemical bonding is more or less a spectrum and does not consist of rigidly distinct types. We would briefly discuss each one.

Metallic bond: A good mental image to help us understand metallic bonds is to picture an 'electron pool'. Atoms seem to 'swim' in this pool of mobile electrons forming bonds. Metallic bonds are similar to covalent bonds in that there is a sharing of electrons, however these electrons are not tightly held to the atoms. Instead they move about from atom to atom in the metal held by the force of attraction between them and the positive ions present. The hardness and conductivity as well as a host of other properties possessed by metals are as a result of the metallic bond.

Hydrogen bond: The hydrogen bond is a relatively weak bond formed between the atoms of hydrogen and those of other elements. These elements are highly electronegative (meaning that they easily give off their electrons to form cations). Such a bond creates a *dipole* (charges that are opposite with similar magnitudes). This is because the electronegative atom is partly negative while the hydrogen atom is partly positive as these opposing poles attract, there is the existence of a hydrogen bond.
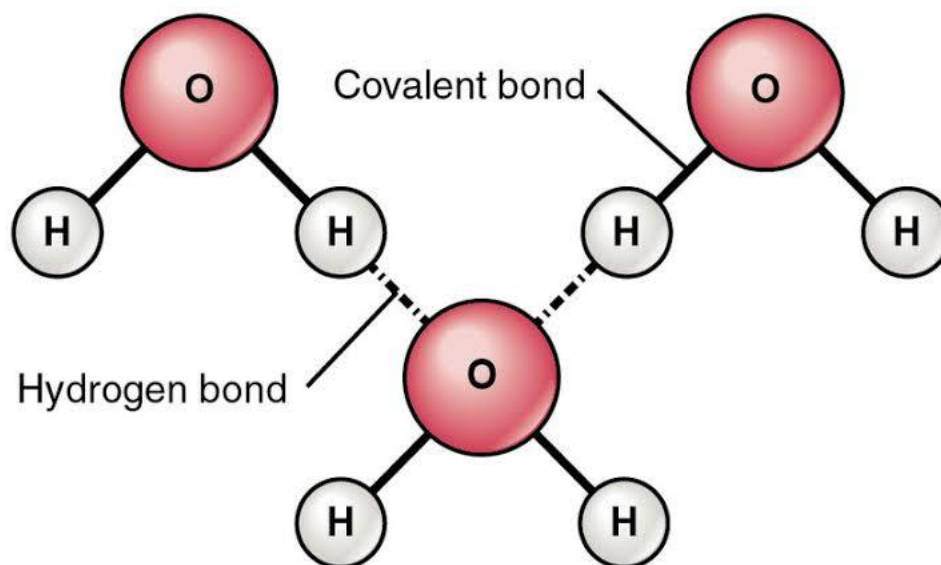
Figure 3-12

Hydrogen bonds are not as strong as covalent and ionic bonds.

Several other forces exist such as the **London dispersion force;** which is on account of swift dipoles occurring in neighboring atoms. It is a significantly weak force. The **cation-pi bond** as the name implies, is a force of attraction between a cation and a pi-bond.**Van der Waals forces** are named after Johannes Diderik Van der Waals who discovered this weak force that is highly dependent on the distance between atoms and molecules. On increasing the distance between atoms, this force breaks down.

Each of these forces are remarkable and can be studied at length. This would be accomplished at another time, when the need arises.

SUMMARY

- Atoms are sociable fellows, hence they bond.

- The octet rule shows that atoms strive to attain the octet configuration of the noble gases.

- Gilbert N. Lewis proposed the Lewis dot structure in 1916 to aid the understanding of atomic bonds.

- Valence electrons are the electrons located on the outermost shell of an atom known as the valence shell. They participate in chemical interactions that involve the atom.

- The screening effect of electrons is a reason why electrons reside in the valence shell of an atom.

- K, L, M, N… are known as principal shells with principal quantum number n, where n is 1,2,3… corresponding to the shell.

- The maximum number of electrons on each shell can be obtained by the formula $2n^2$.

- s,p,d,f are subshells of the principal quantum shells with azimuthal quantum number ℓ, where ℓ is 0,1, 2, 3… depending on the subshell.

- The maximum number of electrons on each subshell is gotten by $2(2\ell + 1)$.

- Writing the electronic configuration is a substitute for drawing shell diagrams.

- Pauli's exclusion principle states that no two electrons can have the same quantum numbers.

- Hund's rule states that in filling orbitals, electrons do do singly first before occupying the orbitals in pairs.

- The Aufbau principle states that electrons occupy orbitals starting from those with the lowest energies to those with the highest energies.

- An electrovalent or ionic bond is a type of chemical bond formed between atoms in which one atom loses an electron to form a positively charged ion (a cation) and another atom gains the electron to form a negatively charged ion (an anion).

- An ion is an electrically charged atom or molecule formed by the loss or gain of an electron.

- A cation is a positively charged ion while an anion is a negatively charged ion.

- Covalent bonds are formed when atoms involved in a reaction share pairs of electrons.

- Three types of covalent bonds are single, double and triple covalent bonds.
- Electrovalent and covalent compounds differ in their properties (refer to *MNEMONICS* after this section).
- Other forces of attraction such as metallic, hydrogen, London dispersion, cation-pi and Van dar Waals bonds exist.

MNEMONICS

Okay. Here we go.

- Properties of electrovalent and covalent compounds:

<p align="center">H   E   B   S</p>

H – Hard: As in "Electrovalent compounds are **hard** but covalent compounds are not**."**

E – Electricity: As in "Electrovalent compounds conduct **electricity** but covalent compounds do not (with a few specific exceptions)."

B – Boiling point: As in "Ionic compounds have high **boiling** and **melting** points but covalent compounds have low melting and boiling points."

S – Solubility: As in "Ionic or electrovalent compounds are **soluble** in water and other polar solvents but covalent compounds are not **soluble** in water and polar solvents but in non-polar solvents."

Can you think up interesting mnemonics with this? How about just 'HEBS'? (similar to herbs) or maybe 'Happy Eels Buy Ships' ? Maybe 'High Electricity Blows Sockets'. Think up creative mnemonics so you never forget.

- Types of chemical bonds:

<p align="center">L   M   C   V   C   H   I</p>

L – London dispersion forces

M – Metallic bonds

C – Covalent bonds

V – Van der Waals forces

C – Cation-pi bonds

H – Hydrogen bonds

I – Ionic bonds

Can you think up interesting mnemonics with this? How about 'London May Choose Very Heavy Ink'? Think of interesting mnemonics so you don't forget.

REVISION QUESTIONS

1. State the following laws:

    a) Hund's rule

    b) Pauli's exclusion principle

    c) The Aufbau principle

2. a) What are valence electrons and valence shells?

    b) Draw electron shell diagrams for the following atoms:

    i.   O

    ii.   N

    iii.   Be

    iv.   H

    v.   Si

    c) How many valence electrons do each of them possess?
    d) Write down their electronic configurations.
3. Briefly explain the following:

    a) Electrovalent bonds

    b) Ionic bonds

    c) Covalent bonds

    d) Anions

    e) Cations

4. In a tabular form list the differences between electrovalent and ionic compounds.

5. What type of bond can be found in the following compounds and molecules:

    a) H_2O

    b) N_2

    c) I_2

    d) NH_3

    e) CH_4

6. Draw spin diagrams for N, O and F.

7. List and explain seven types of chemical bonds.

8. [Ar] $3d^{10} 4s^1$

    a) What atom has the configuration above?

b) How many valence electrons does it possess?*(If you get this, you're a budding Einstein. Put on your thinking cap and give it a try).*

9. Why do atoms attain stability?

10. Write the electronic configuration for oganesson (Og) with atomic number 118. *(Don't cry. This isn't a compulsory one but it helps so you practice).*

CHAPTER 4: MATTER

In chapter 3, we spoke about how everything around us is made from atoms and molecules. Without atoms there would be no forms. All the things around us would not be there. A construction worker cannot build without materials. The materials of things are atoms. We already know that in order to form these things atoms must bond with each other. As they bond, they form **matter.** So the question now is; what's the matter with **matter**? (Don't cringe. Already did that for the two of us).

Anything that we can see and touch is matter. The desk on which I am typing, the chair I am sitting on, the book you are reading, the bed you sleep in, the food you eat, your classmates, the birds, the trees, your mum, US president Trump (at the time of this writing), John Cena, everything and everyone that we can see and touch is matter.

"Matter is anything that has weight and occupies space."

If you can see that it weighs something and it takes up space, then it must be matter. This means that even gases such as the air we breathe are considered matter. Before you frown disapprovingly, know that air has weight. You can feel it; molecules of it. Air also takes up space. You can contain gasses in vessels and they would take up the whole space inside. You would come to understand all these in this chapter.

The states of matter

Again, I repeat that I am no psychic but I think that you are probably reading this book indoors. I think now is a good time to go outside unless of course you are in class. In that case just ask for permission. I am certain you are not reading this during lesson hours even though that may leave me flattered. Still, don't do it. If you can, go outside. When you get outside, look around. What can you see? Are there any trees around? Any hard surfaces? Find a hard surface like a concrete block. Make observations based on its texture, appearance and so on. Now find some water. Could be from a tap. Run it through your fingers and observe. Finally, breathe in, and then breathe out blowing air forcefully with your fingers held in front of your hands and feel the air that comes rushing out of your mouth.

Hardened solids

When you felt the hard surface what did you observe? If you had exerted significant force you may have just broken your hands and blamed my book for it (which your teachers won't take likely). Solids are just so. They are really put together and compact. What do you think is responsible for this? We have said that atoms and molecules are the building blocks of all things so naturally atoms and molecules make up hard things too including the concrete. They are all joined together in the solid via chemical bonds forming the structure that you can see. The reason they are hard is that the atoms in each molecule of the solid substance are tightly packed in dense structures. Since they are all so held together, there is little freedom for movement available and so their positions are rigidly fixed. That's why when you hit a solid surface with your hands the surface doesn't become distorted and fall away easily even though I can't say the same thing for your hands (your hands are considered solid though). One can almost hear the little atoms screaming in tiny voices; "United we stand!"

Now you are probably wondering why some solids do break away slightly when you hit them hard. It is true that they do, but relative to the other states of matter they are more severely held together. A chip or two may fall but a solid material seldom collapses totally and in fact you may just get tired of trying to break it. In other terms, solids can be *hard to compress*. For this very reason it is very difficult to fill a containing vessel with a solid of a definite shape. Imagine trying to fit a rectangular cement block into a milk bottle without altering it! I am quite sure that's impossible. This is because solids have *specific volumes*.

Solids are also of different kinds. Some solids have stronger bonds that hold their atoms together such as ionic bonds. These bonds allow for a more rigid and crystalline solid structure. Weaker bonds such as van der waals forces between atoms leads to the formation of less rigid structures, nonetheless relatively tightly packed. These structures are termed *amorphous*.
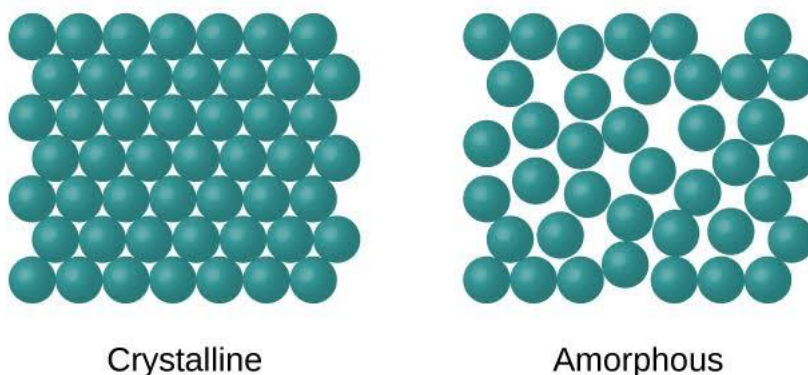

Crystalline   Amorphous

Figure 4-1 Crystalline and amorphous solids

Flowing liquids

It is raining right now. Sometimes when it rains I usually feel tempted to just go stand under it. I can't swim, so I'm thinking it's the closest I might get to surrounding myself with water. Been years I did anything like that though, and I love seeing kids do that. But I remember very vividly that it felt good to stand under the rain. You only had the tap water run through your fingers (at least I'm hoping it was only your fingers) but I'm guessing it felt good. It's one reason taking a shower feels good too. The water just slid past your fingers fairly easily. It wasn't so rigid like a block of cement. Imagine having a 'cement shower'. You may not live. This apparent 'softness' of water may seem surprising when we think of the solid. I mean, they are both made of atoms so why are there so different? This happens because the atoms in the liquid molecules are not so rigid and keen on 'uniting' like the atoms of a solid. They are a little loose, meaning they can wiggle around a little. They are still held together by bonds but have some freedom.

When chemists refer to this wiggling action they call it *translation.* The particles that make up liquids can translate a little more than solids and that's why they can flow but solids can't.

Another thing substances in the liquid state can do is occupy the volumes of the containers they are put in. Remember how ridiculous we said it would be to attempt putting a rectangular cement block into a milk bottle? Liquids do not have this problem. You can *pour* a liquid into a vessel and it would easily go in. This means they can be compressed and do not have definite shapes and volumes.
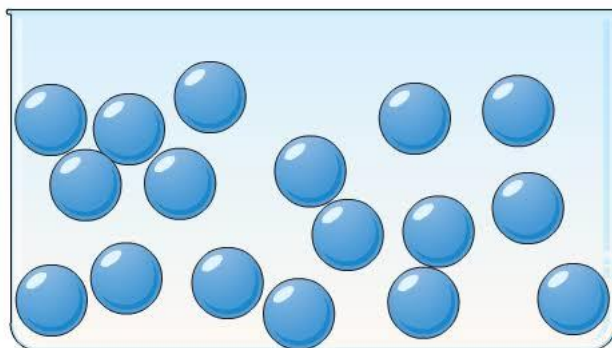

Figure 4-2 The liquid state.

Free gases

Did you feel the air between your fingers? How quickly did it blow away? Could you catch it? Must have been hard since unlike liquids and solids gases go by very quickly and cannot be held. Even though liquids flow, you could at least hold some of that tap water in the palm of your hand. Gases however cannot be handled in the same way. You may have already guessed the reason why.

Gases are composed of atoms and molecules just like solids and liquids, but while the particles (atoms, molecules and other entities) of liquids and solids are held together to varying degrees, gaseous particles are held together least of all and are freer to wander about. They have no restricted shapes and volumes but like liquids, fill up the volumes of the containers they are put into, colliding with the walls and moving in every direction. This shows that they can be compressed even though they are separated by large distances.
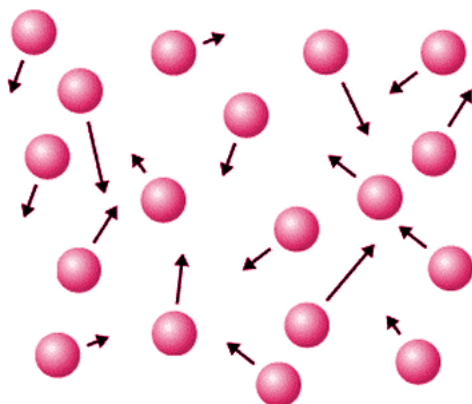
Figure 4-3 Gaeous state of matter.

It may sound funny, but I have always loved to picture these three states of matter as siblings; the solid state being the zealous, uptight responsible elder sibling, the liquid state the less uptight middle child with traits from the other two and the gaseous state the wild and crazy last born. This helps reinforce the picture of their characteristic bonds. It's good to have a little fun with chemistry.

When the states go changing

Atoms and molecules love to play tricks and one of their favorite tricks is changing things from one form to another. Try doing this so you have a first class view of the show.

Take an ice tray or any container that can hold water. Put some water into this container. Place the container with the water in it into a freezer and wait. Go watch your favorite show perhaps. After sometime, check the container. What can you observe? Place the container in a pot of some water on the stove and light the stove (for only a brief period of time!). After a while check the container. Did anything change?

I am sure this is a process you are already familiar with. However the difference this time is that we are going to know exactly what's going on with chemistry.

As you took the bowl of water it was in the liquid state. When you placed it in the freezer and went on to finish watching *Master Chef* something was definitely going on because you came back later and saw that the water had become hard. On heating the water in the container it reverted back to the liquid state and then changed yet again into steam, which is in the gaseous state. As you removed the container from the heat, you must have started noticing that there were droplets on the body of the container. This single container of water had gone about changing state a number of times while you watched your show. So what's happening here?
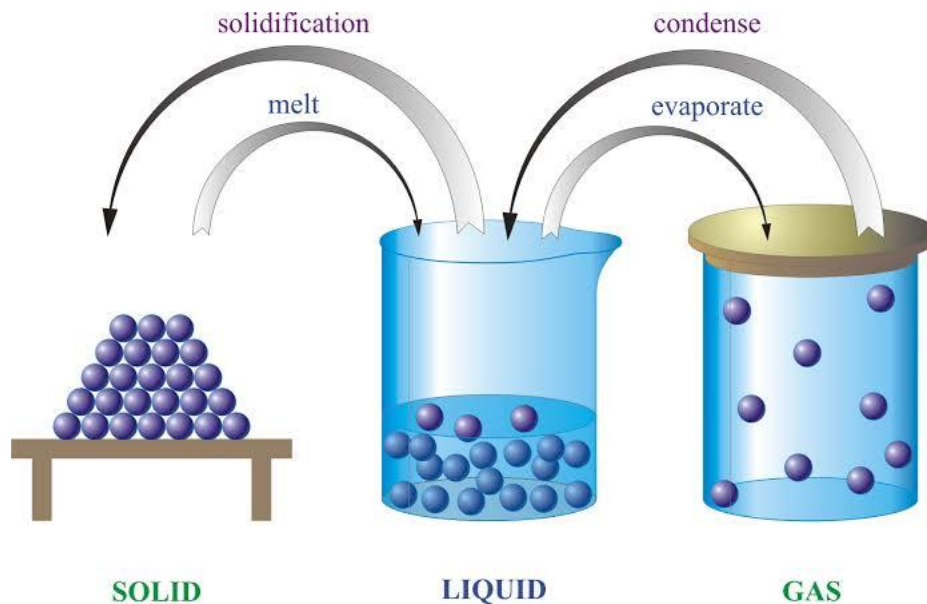
Figure 4-4 Change of state.

When you placed the water in the freezer, the water molecules underwent a process known as **solidification** or **freezing.** The water molecules on cooling fused together when the water had reached its *freezing point.*

"The freezing point of a liquid is defined as the temperature at which the liquid changes into a solid on being cooled."

When you had taken the water from the freezer and heated it, you noticed that it had now become a liquid again. The process by which this occurred is called **melting.** The solid structure of the ice became less rigid and collapsed as heat was applied allowing the molecules to translate and change state from solid to liquid at a special temperature known as its *melting point.*

"The melting point of a solid is the temperature at which the solid changes into a liquid."

Melting happened because the molecules of the water had obtained sufficient energy in the form of *kinetic energy* and could now move about more freely. In the absence of boiling, the water would still melt because there is sufficient heat to ensure this. It would only be much slower.

"Kinetic energy is defined as the energy acquired by a particle on account of its motion."

Kinetic energy can be increased by particles in a containing vessel when sufficient energy in the form of heat is applied. The particles therefore alter their properties because of this.

A unique aspect of melting is in a process known as **sublimation.** Here, solids change directly to the gaseous state without passing through the liquid state. It happens at a certain temperature and pressure known as a substance's *triple point* and unique to that substance, which is the lowest pressure at which it can exist as a liquid. Sublimation is then easier to attain for the substances since it is difficult to reach the triple point. Examples of substances that sublime are dry ice (solid CO_2) and Iodine.

Back to our container of melted ice. On boiling you may have observed small droplets of water escaping. These droplets are known as *vapour* and the process by which they are formed is called **evaporation.**

"Evaporation is the process by which liquids change into the gaseous state."

Even though we **boiled** the water, we did not have to for evaporation to take place. As you know, water consists of molecules. These molecules are arranged in such a way that they are surrounded by each other and hence exert forces on each other. The implication of this is that the liquid surface appears stretched out like some tightly held material. This therefore ensures that the liquid molecules cannot escape easily.

When the molecules acquire sufficient kinetic energy however either through boiling or some other means, molecules within the body of the water then possess enough energy to break out of the water and when they do, they escape as vapour into the atmosphere. That's what you see, and it is the gaseous phase of water after undergoing the evaporation process.

We have already mentioned that evaporation can occur without boiling, however it occurs at a faster rate when boiling is included. The *vapour pressure* of the gas also increases in the process. Once this happens the vapour then **condenses** back into the liquid state.

"Vapour pressure is defined as the pressure exerted by the vapour of a liquid on the walls of a containing vessel over the surface of the liquid."

When the water was boiled, the vapour that escaped was colliding with the container's walls and with each other. This hitting about naturally produced some sort of pressure. That pressure is what is known as the vapour pressure.

"Condensation is the process by which a liquid changes into a gas."

As the vapour collided with the container's walls they entered the liquid again, changing into the liquid state. If you allowed this process to continue, a point would have been reached where the number of molecules evaporating would be equal to the number of molecules condensing. When this happens the liquid can be said to reach a *saturated vapour pressure.*

And so that ends the chronicles of our container of water. Now we would be examining two states of matter that are a little less known.
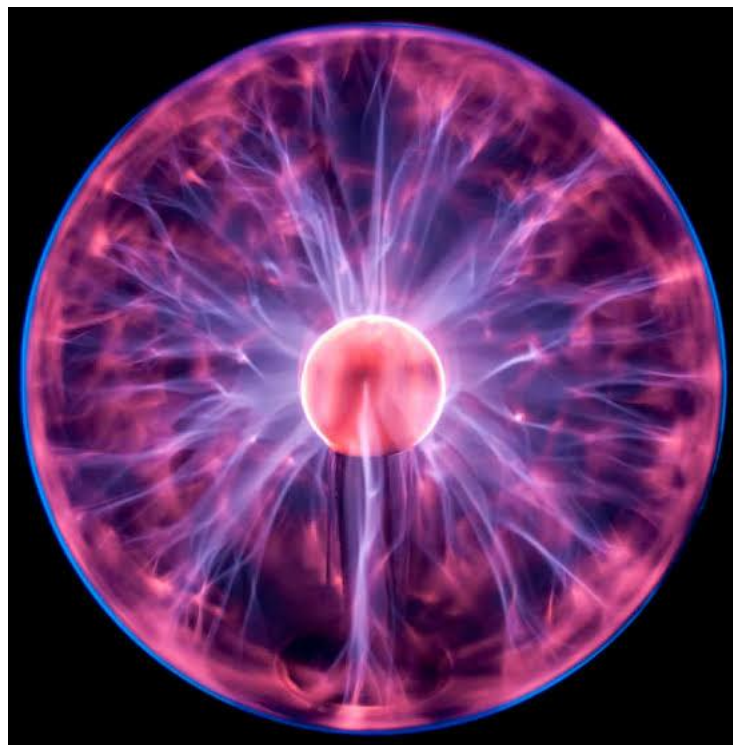
Electrical plasma

Figure 4-5 Plasma

It would have been nice to ask you to go outside and feel the texture of plasma, but unfortunately that would most likely not occur. Unlike solids, liquids and gases, plasma is a little less easy to find. For a long time it was believed that even though plasma seemed to differ from gases it showed similarities that made it seem like a kind of gas. For instance just like gases, it has no defined volume and shape and can move about. However the plasma state of matter is far from the gaseous state. Gases consist of atoms which are mostly neutral but plasma consists of atoms that have few or no electrons at all. That sounds like the sort of crazy atoms would put out for us. So unless you've got a super charged gas somewhere outside and can touch and breathe it in without dying, I suggest you stay in to read instead unless it's a beautiful day outside. We know that atoms can lose and gain electrons and in so doing form ions. Plasma consists of these charged atoms and due to this reason it mostly exists in bodies like the sun and other stars. It is really popular out there but not so much on earth because it requires certain conditions. Matter on earth is largely neutral (thank God for that) but in harsh conditions of space ions drifting about in large fusion reactors that are the stars are not hard to spot. If you are wondering what fusion reactors are, don't worry as you would find out later. For now, just know that the surfaces of stars are really 'violent' and just the place the charged, electron stripped plasma would feel right at home. This does not imply that plasma is absent on earth. Plasma has practical use in Television sets, neon signs and fluorescent bulbs and can be found naturally in the *aurora;* that beautiful stream of lights found at the poles; any place with the right conditions to induce ionization.

Gases differ greatly from plasma, so it would do us good to differentiate between them so we don't go breathing in the wrong thing (by the way, there are several toxic gases on earth).

Gases	Plasma
1. Composed of neutral atoms.	Composed of ions with a few or no electrons
2. Do not conduct electricity except in special conditions such as in lightening storms.	Since they are composed of ions and electrons, they conduct electricity.
3. Gas particles collide with one another and with the walls of	Plasma ions have too low densities to be said to collide hence their interactions are

their containing vessel.	electrostatic and magnetic in nature.
4. Gases are dealt with in regards to particles.	Plasma is largely analyzed with regards to waves such as the *Alfven waves.*

Table 1. Differences between the gas and plasma states of matter.

Mysterious Bose-Einstein Condensate

Sometimes in chemistry what sounds like science fiction isn't fiction at all. That is what makes the mysteries all the more strange and I dare say more interesting. All the states of matter we have discussed above have been known for quite a long time. This state of matter however was only created in the 'pure' form by Eric Cornell, Carl Wieman and some others at JILA in 1995 (You could read on this). It was however predicted by two great scientists; Satyendra Nath Bose (who the boson particle is named after) and Albert Einstein.
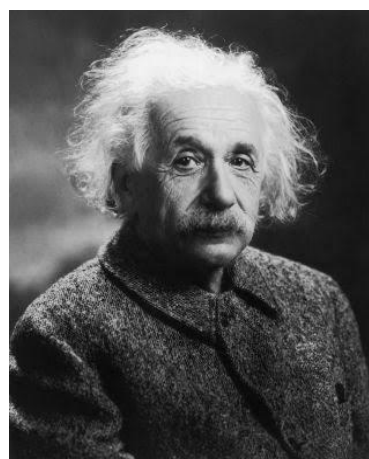

Figure 4-6 Satyendra Bose (left) and Albert Einstein (right).

A bose-Einstein condensate consists of a group of atoms cooled to a very low temperature known as the *absolute zero;* which is according to theory, the lowest temperature can be possibly reached. At this temperature the subjected atoms cease moving about so much, which is unusual since atoms are always in motion. Then they suddenly begin to do a most remarkable thing. They start coming together in clumps and the many atoms appear to become a single atom; some mother of Frankenstein atom. They essentially stop being separate bonding atoms and begin to act as just a singular atom, all atoms becoming identical in their properties and acting alike. If this isn't more like science fiction and less like reality to you, I don't know what is. Remember Pauli's exclusion principle? Usually in the world of science when something is identified as a **law** or a **principle** it usually means that it has gone through extensive

tests in the hands of so many researchers and has beaten all opposing views and resistances coming out on top. Nature really doesn't care about that and the atom is sure to remind us of this fact every time.

Even though Pauli's principle can be applied everywhere else that we know, when it comes to the Bose-Einstein condensate, this law fails considerably. This is because the law explains that no two atoms can have the same four quantum numbers (be alike) and so all atoms are unique. However, as seen from the Bose-Einstein condensate, all the atoms become **identical** and possess the **same quantum numbers**. I guess this means there are exceptions to Pauli's law.
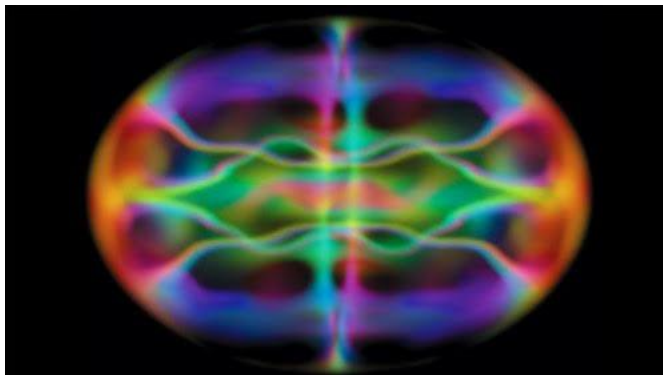

Figure 4-7 The Bose-Einstein condensate

In order to create this in the laboratory, scientists subject a group of atoms (in gaseous state) to cooling with lasers. They then proceed to cooling by evaporation. Once cooled sufficiently, the Bose-Einstein condensate is formed.

Now that we have seen the five states of matter in existence (at least for now), we would proceed to learning even more about the gaseous state as there are a lot of interesting things to know.
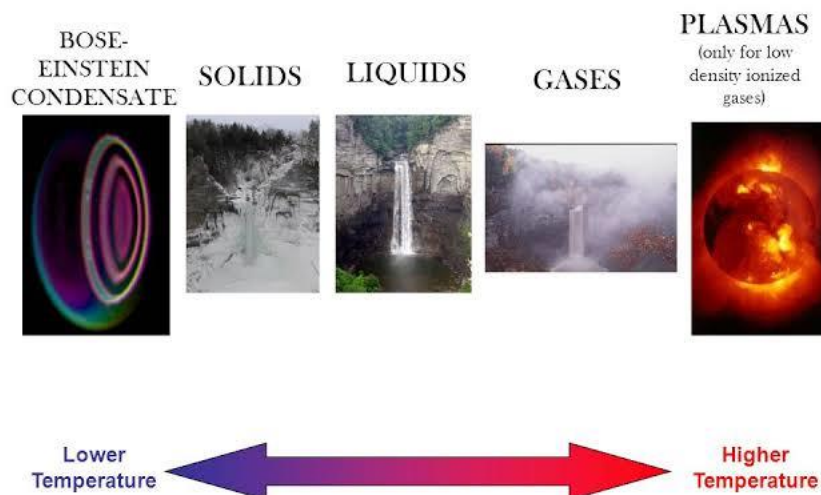
The _five_ states of matter:

Figure 4-8 The five states of matter and the temperatures in which they exist.

Gas Laws

By now I'm sure you are aware that scientists talk about laws a lot. This is because they are trying to find out how the world works and the things that govern all that exists. Gases have quite some unique characteristics and hence have piqued the interests of scientists for many years. Here we would be studying the postulates proposed by some of these great men and women as a result of their studies. But first, we would have to introduce an important concept known as the **kinetic theory of gases** by listing the elements of this important theory.

The kinetic theory of gases:

1. Gases are composed of particles (atoms and molecules) that move about constantly and randomly.

2. In moving about these particles are always colliding with each other and with the walls of their containing vessel. The collisions that occur are perfectly _elastic_ (meaning that no energy is lost from the interactions).

3. In comparison to the volume of the containing vessel, the volume that the gas particles occupy is so small that it may be considered negligible.

4. There are no forces of attraction or repulsion between the particles.

5. The temperature of the gas is a measure of the average kinetic energy of the gas particles hence all gases at the same temperature have the same average kinetic energy.

The above apply to an *ideal* or *perfect* gas, which is essentially a gas that follows all the above laws. Actual gases however, show some deviation from this.

Let's move on to the gas laws and the people to whom we show gratitude for them.

The Boyle-Mariotte Law

Volume-pressure relationships concerning gases had been observed firstly by Henry Power and Richard Towneley but lacked experimental backing. That was where two scientists came in who stated the law independently of each other even though it is widely known as Boyle's law in most chemistry texts. This is probably because Robert Boyle had published his findings in 1662, while Edme Mariotte had published his years later in 1679 unaware of Boyle's advance. It is interesting to know that the apparatus that was used was built by another great scientist, Robert Hooke.
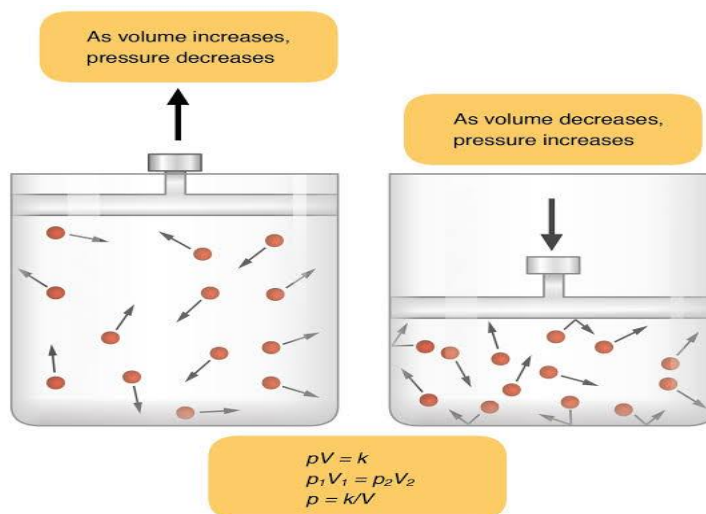

As volume increases, pressure decreases

As volume decreases, pressure increases

$$pV = k$$
$$p_1V_1 = p_2V_2$$
$$p = k/V$$

Figure 4-9 Illustrating the Boyle-Mariotte law

You are already aware of the concept of gaseous pressure which we talked about when we examined the states of matter. We spoke of gas particles acquiring more kinetic energy on being heated and moving about quicker, colliding with each other and the walls of the vessel. We called the sum of these collisions the pressure of the gas. Even in the absence of heat, we learnt that gasses have pressure. We are also no strangers to volume, which we said was the space occupied by the gas molecules. The above image just illustrates these. The kinetic theory can show what's going on here. We find a containing vessel with a piston undergoing two stages. At first in the vessel we see that the gas particles have occupied a large volume. On account of this they move about more slowly because they is more space to move about as the number of collisions on each unit area is small hence

they have **lower pressure** on account of the **larger volume**. However when sufficient force is placed on the piston and the gases now contend with a **lower volume,** they are forced to collide with each other more frequently and with the walls of the container as well. The number of collisions exerted for each unit area now rises. This means that they now have a **higher pressure.** This only holds at a constant temperature.

Picture this. School is over and you go into the school bus with your friends. At first when you enter the bus, you find seats fairly quickly and are seated comfortably. People need to come in contact with each other less because there is more space to move around. Even your class clown friend Tunde can get up and dance around the bus like a ballerina without having to touch anyone. Fifteen minutes have now elapsed. More students have entered the bus. It is becoming increasingly difficult for Tunde to dance now without hitting anyone. Oh and you forgot about the visiting school band that has to share the bus with you! The place has become so crowded now that you can't move your hands without giving someone a slap by accident. When there were only a few people in the bus, you could say that there was more *volume* hence each person could occupy more space. This also meant that you didn't have to be so close to other people, corresponding to *less pressure*. When the bus became congested and Tunde couldn't dance anymore, the space allocated to each person reduced significantly meaning *less volume so* everyone became so close to everyone else that we could say *pressure increased* (in more ways than one).

Can you notice the interplay here between pressure and volume? As volume increases, pressure reduces and as volume reduces, pressure increases. This is the Boyle-Marotte law.

"The Boyle-Marotte law states that the volume of a given mass of gas at constant temperature is inversely proportional to its pressure."

It can also be shown mathematically as:

$$V \propto \frac{1}{P}$$

$$V = \frac{X}{P}$$

$$PV = X$$

$$P_1V_1 = P_2V_2$$

Where V = Volume

P = Pressure

X = Mathematical constant

P_1,V_1 = Initial pressure and volume

$P_2,V2$ = Final pressure and volume

Charles' Law

This law was formulated by French scientist Jacques Charles in the 1780's. It is a law that shows the relationship between the volume and temperature of a specified mass of gas. An interesting fact here is that Charles' law was never actually published, but was brought to light by John Dalton in his 1801 paper where he explained it and attributed its origin to Jacques Charles. That's a really good guy thing to do because some scientists have been known to be less than honest.
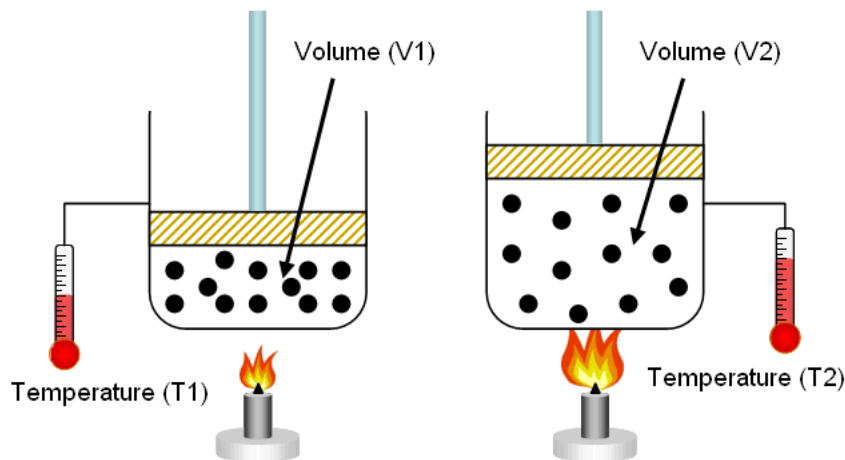

Figure 4-10 Charles' law illustrated

Figure 10 above consists of two stages of the same process just like figure 9. Here we have introduced heat at the bottom of the containers and have a thermometer standing by to, measure the temperature of the system. The piston used here is very light and in fact its weight is considered negligible for the purpose of this experiment.

On moderate heat we notice that the piston is moved up only slightly and the gas molecules are more closely packed hence they occupy less volume. When the heat is increased, we observe that the molecules push up the piston considerably and the volume occupied by the gas is increased.

We can harness the postulates of the kinetic theory to explain this as well. The molecules of the gas on heating obtain more kinetic energy and can move about faster, colliding more with each other and the container walls. As they move, they push the piston upwards because they need more space to move about. It's like feeding small children a lot of sugary treats and placing them in a small room. Chances are with all the hyperactive energy they get from the candy they may be itching to get out and run around. You should then probably open the door for your own sake. What this shows is that when the temperature increases, the volume increases and when the temperature falls the volume falls as well at a constant pressure.

"Charles' law states that the volume of a given mass of gas is directly proportional to its temperature in Kelvin, as long as the pressure remains constant."

Mathematically this is;

$$V \propto T$$
$$V = XT$$
$$\frac{V}{T} = X$$
$$VT = X$$
$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Where V = Volume

T = Temperature (in Kelvin,K)

X = Mathematical constant

V_1, T_1 = Initial volume and temperature

V_2, T_2 = Final volume and temperature

You have seen *temperature in Kelvin* and you are probably wondering what that means. Just like the Celsius and Fahrenheit scales, the Kelvin is a unit of temperature. It is based on the absolute zero temperature.

"The Kelvin scale is a temperature scale in which the absolute zero is taken to be its starting point (0K) and is equivalent to -273.15°C.

If you recall the absolute zero, you would remember that it is the lowest possible temperature attainable by a substance and below this temperature all movements cease. This absolute zero is the beginning of the Kelvin scale and it corresponds to -273°C.

$$0K = -273.15°C.$$
$$0°C = 273.15K$$

This therefore means that;

$$T(K) = T(°C) + 273.15$$
$$T(K) = \text{Temperature in Kelvin}$$
$$T(°C) = \text{Temperature in Celsius degree}$$

Now you can convert from the Celsius to Kelvin temperature scale and vice versa. Memorize this well because we'll be using it quite a lot from now.

The Pressure Law

There is some argument as to who was the originator of this law. It is popularly attributed to Gay-Lussac; however it was initially formulated by the French scientist Guillaume Amontons. He had investigated the law first but found it hard to make accurate measurements on account of not having precise thermometers, but he lay the groundwork for further investigation, which Gay-Lussac explored. It is therefore not entirely wrong to consider this law **Amonton's law** sometimes.

This law investigates the relationship between the pressure and temperature of a fixed mass of a gas at a constant volume.
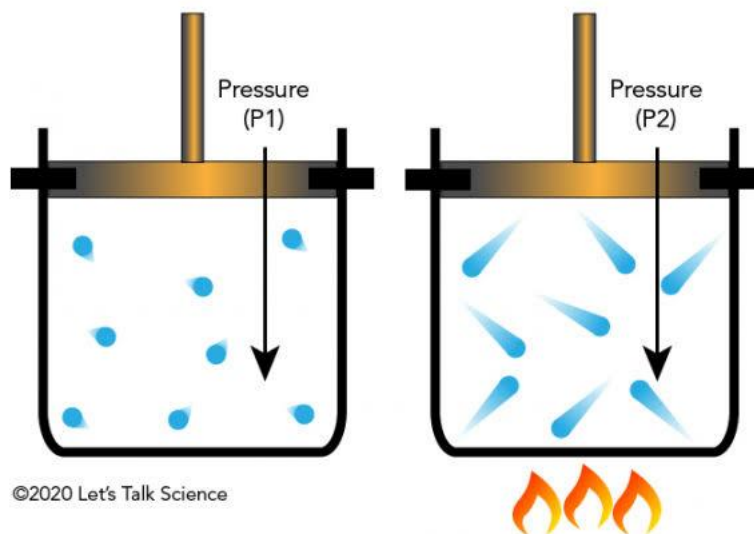
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Figure 4-11 Pressure law (or Amonton's law)

In the first container we notice that no heat is applied. The gas molecules are moving about more languidly. There are fewer collisions with each other and with the walls of the container. This means there are few collisions per unit area of the container. This means there is low pressure. When heat is introduced, this story changes. The gas molecules are now seen to move much faster and collide much more frequently. Their collision per unit area has increased and this therefore means that their pressure has definitely increased. So we see that when the temperature increases, the pressure increases and when the temperature falls, so does the pressure. The two are hence directly proportional. How can this be explained by the kinetic theory? Easy. We've explained it before. As the molecules acquire energy supplied by the heat in the form of kinetic energy, they move about much more hitting each other and everything in their path including the container walls. Remember sugar-fed children?

Figure 4-12 More energy equals more collisions which equals more pressure.

"The Pressure Law states that the pressure of a given mass of gas is directly proportional to its temperature in Kelvin, provided the volume is kept at a constant."

Mathematically this is;

$$P \propto T$$
$$P = XT$$
$$\frac{P}{T} = X$$
$$PT = X$$
$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Where P = Pressure

T = Temperature (in Kelvin,K)

X = Mathematical constant

P_1, T_1 = Initial pressure and temperature

P_2, T_2 = Final pressure and temperature

Avogadro's Law

Remember our old friend Amedeo Avogadro without whom we would never have known that one mole of every gas contained 6.022×10^{23} elementary entities? That knowledge we got is also very crucial when analyzing gases. In order to have more accurate calculations, we speak of the volume of the gas in terms of the mole, which I'm sure you recall. We would now restate Avogadro's law to refresh your memory.

"Avogadro's law states that equal volumes of all gases at the same temperature and pressure contain the same number of entities or units."

These entities can be atoms or molecules. Mathematically, the law can be stated thus:

$$V \propto n$$

$$\frac{V}{n} = X$$

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

Where V = Volume

n = amount of substance of the gas (in moles)

X = Mathematical constant

V_1, T_1 = Initial volume and amount of substance

V_2, T_2 = Final volume and amount of substance

What this law shows is that if you increase the volume of a mass of gas the number of moles of that gas that would increase and if you reduce the volume of the gas, the number of moles of the gas would fall likewise.

The General Gas Equation

When the Boyle-Marriotte law, Charles' law, the pressure law (Amonton's law) and Avogadro's law are taken together, the resulting equation is known as the **General gas equation.** This is because in any system of gasses the four variables of pressure, volume, temperature and amount of substance are at play. Since these laws are formulated on the basis of the kinetic theory and hence describe an ideal gas, the general gas equation is also known as the **ideal gas law.**

"The ideal gas law states that the volume of a given mass of gas is directly proportional to the number of moles it contains and its temperature in Kelvin but inversely proportional to its pressure."

Mathematically;

$$V \propto \frac{nT}{P}$$

$$V = \frac{nRT}{P}$$

$$PV = nRT$$

$$R = \frac{PV}{nT}$$

Where V = Volume

P = Pressure

T = Temperature

n = amount of substance of the gas (in moles)

R = Molar gas constant

In some problems you would be required to solve, consideration of the molar gas constant (R) and the amount of substance in moles (n) would not be required of you. In those situations you would only need to combine the Boyle-Mariotte law, Charles' law and the pressure law to give:

$$V \propto \frac{T}{P}$$

$$V = \frac{XT}{P}$$

$$PV = XT$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Where P = Pressure

V = Volume

T = Temperature (in Kelvin,K)

X = Mathematical constant

P_1, V_1, T_1 = Initial pressure, volume and temperature

P_2, V_2, T_2 = Final pressure, volume and temperature

Gay-Lussac's Law of Combining Volumes

We are revisiting a new friend. I find such moments pleasing. Joseph Louis Gay-Lussac had formulated this law in 1808. He aimed to find out the proportions (volumes) in which gases combined.

"Gay-Lussac's law of combining volumes states that when gases react they do so in simple whole number ratios to each other and to their products as long as temperature and pressure remain constant."

Gay-Lussac's findings are responsible for the 'chemistry fever' that struck Avogadro from which he formulated his law.

For instance by balancing the equation below we know that if we combine 1 volume of nitrogen (N_2) and 3 volumes of hydrogen (H_2) we get 2 volumes of ammonia (NH_3). According to this law this can be shown as 1 molecule of N_2 combines with 3 molecules of H_2 to give 2 molecules of NH_3.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

The ratio of the combining volumes is 1 : 3 : 2

Dalton's law of partial pressures

You certainly cannot forget the stylishly posing John Dalton who had defined what the atom is. He noted this law in 1801 and published his findings in 1802. The law shows that for a mixture of gases that do not react, their total pressure can be obtained by adding the pressures of the individual gases that make up the mixture.

"Dalton's law of partial pressures states that the total pressure exerted by a mixture of gasses that do not react with each other can be gotten by adding the individual pressures of the individual gases that make up the mixture."

Mathematically for a mixture of n gases;

$$P_{total} = P_1 + P_2 + P_3 + P_4 + P_5 \ldots + P_n$$

Where P = Pressure

Graham's Law

Scottish Chemist Thomas Graham made a proposition based on an observation in 1848 that has now become a law. This law is known as **Graham's law of effusion (or diffusion).**It is based on a concept known as the **vapor density** of a gas.

"The Vapour density of a gas is defined as how heavy a certain volume of a gas is in relation to the same volume of hydrogen under the same conditions of temperature and pressure."

Just like we noted when coming to terms with the mole, we also see here that we must have a standard (in this case hydrogen) to make accurate measurements in chemistry. Mathematically;

$$V.D = \frac{Mass\ of\ volume\ of\ gas}{Mass\ of\ equal\ volume\ of\ hydrogen(H)}\ (T\ and\ P\ constant)$$

The relative molecular mass of a gas can be related to its vapour density as shown below:

$$V.D = \frac{Mass\ of\ n\ volume\ of\ gas}{Mass\ of\ n\ volume\ of\ H}$$

Graham's law suggests that 1 volume of a gas can be expressed as 1 molecule of the gas so that;

$$V.D = \frac{Mass\ of\ n\ molecules\ of\ gas}{Mass\ of\ n\ molecules\ of\ H}$$

So;

$$V.D = \frac{Mass\ of\ n\ molecules\ of\ gas}{Mass\ of\ n\ molecules\ of\ H}$$

A molecule of hydrogen consists of 2 atoms;

$$V.D = \frac{Mass\ of\ 1\ molecules\ of\ gas}{Mass\ of\ 2\ atoms\ of\ H}$$

$$2 \times V.D = \frac{Mass\ of\ 1\ molecules\ of\ gas}{Mass\ of\ 1\ atom\ of\ H}$$

Relative to hydrogen;

$$\frac{Mass\ of\ 1\ molecules\ of\ gas}{Mass\ of\ 1\ atom\ of\ H} = Relative\ molecular\ mass\ of\ the\ gas$$

$$2 \times V.D = Relative\ molecular\ mass\ of\ the\ gas$$

And now we see that the relative molecular mass of a gas is twice its vapour density. Graham's law determines how this density and the effusion (or diffusion) rates correspond. His experiments consisted of racing gases against each other and making observations and calculations while doing so, probably eating popcorn because the races were just too thrilling. He learnt that the rates at which gases effused was in inverse proportion to the square roots of their vapour density.

"Graham's law states that the rate of effusion (or diffusion) of a gas is inversely proportional to the square root of its vapour density provided temperature and pressure are kept constant."

Mathematically;

$$R \propto \frac{1}{\sqrt{V.D}}$$

$$R = \frac{X}{\sqrt{V.D}}$$

$$R\sqrt{V.D} = X$$

$$R_1\sqrt{V.D_1} = R_2\sqrt{V.D_2}$$

$$\frac{R_1}{R_2} = \sqrt{\frac{V.D_2}{V.D_1}}$$

Where R = Rate of effusion (or diffusion)

V.D = Vapour density

X = Mathematical constant

$R_1, \sqrt{V.D_1}$ = Rate of effusion and vapour density of first gas

$R_2, \sqrt{V.D_2}$ = Rate of effusion and vapour density of second gas

If writing V.D too frequently seems like too much effort for you, you could substitute it with ρ, which is the mathematical symbol for density. The above equation then becomes;

$$\frac{R_1}{R_2} = \sqrt{\frac{\rho_2}{\rho_1}}$$

Graham's law can also be stated in terms of its molecular mass since there is a direct proportion between vapour density and relative molecular mass;

"Graham's law states that the rate of effusion (or diffusion) of a gas is inversely proportional to the square root of its relative molecular mass provided temperature and pressure are kept constant."

This means;

$$R \propto \frac{1}{\sqrt{M}}$$

$$R = \frac{X}{\sqrt{M}}$$

$$R\sqrt{M} = X$$

$$R_1\sqrt{M_1} = R_2\sqrt{M_2}$$

$$\frac{R_1}{R_2} = \sqrt{\frac{M_2}{M_1}}$$

Where M is the relative molecular mass with M_1 and M_2 being the relative molecular masses of the two gases involved.

Henry's Law

William Henry's law is one that isn't always mentioned in secondary level chemistry texts but it is an important law nonetheless and can be observed in everyday experiences. This law is concerned with gas pressures in liquids.

"Henry's law states that the amount of a gas dissolved in a liquid is directly proportional to the partial pressure of the gas above the liquid at a constant temperature."

The law can also be restated as "*the solubility of a gas in a liquid is directly proportional to its partial pressure above the liquid.*" This because solubility of a gas is a measure of the amount of the gas that can dissolve in a liquid.

You can observe the effects of Henry's law when you open a carbonated soft drink like a can of coke or fanta. Carbonated drinks contain carbon dioxide. Before we open the drinks to enjoy their sugary goodness, carbon dioxide that is almost pure settles at their surface at a pressure that exceeds the atmospheric pressure (the pressure exerted by the atmosphere or the surrounding air). In accordance with Henry's law the solubility of the CO_2 in the can is also high. When you open the can or bottle, the contained carbon dioxide in the can rushes out (hence the hissing sound) and lowers the partial pressure of the CO_2 resting on the surface. The reduced CO_2 pressure on the surface means that the solubility of the CO_2 in the can also falls. For this reason the CO_2 comes up to the surface of the bottle or can (those are the tiny bubbles you see). When left open too equilibrium between the CO_2 in the can and the CO_2 in the atmosphere would cause the 'fizziness' of the drink to go away.

Every time you have a bottle or can of a cold carbonated drink, remember William Henry and his law. I'll put up a picture here to help.
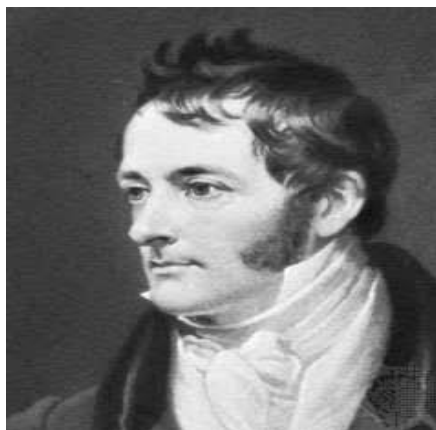

Figure 4-13 William Henry

Mathematically Henry's law can be stated thus:

$$C \propto P$$

$$C = k_H \times P$$

Where C = Concentration (solubility) of the dissolved gas in the liquid

P = Partial pressure of the gas above the liquid

K_H = Henry's law constant

Amagat's law of partial volumes

We had spoken about partial pressures a while back. Now we are going to talk about how the individual volumes of gases results in the total volume of the gas mixture. It was formulated by Emile Amagat. Just like Dalton's law with gas pressures, it simply shows that the total volume of a mixture of gases can easily be gotten once the volumes of the individual gases that make up the mixture are known.

Amagat's law of partial volumes states that the total volume occupied by a mixture of gasses that do not react with each other can be gotten by adding the individual volumes of the individual gases that make up the mixture provided temperature and pressure remain constant."

Mathematically for a mixture of n gases;

$$V_{total} = V_1 + V_2 + V_3 + V_4 + V_5\ldots + V_n$$

Where V = Volume

Real Gas Laws : Van Der Waals' equation of state

So far we have been elucidating the gas laws on the basis that the gases observed obey the kinetic theory of gases and hence are ideal. What happens when we have to analyze a real gas instead? As stated earlier real gases show deviations from the kinetic theory and hence from the ideal gas law. For this reason an old friend of ours

decided that it was time to tweak the idle gas laws so they could apply to real gases. This friend is Johannes Diderik Van Der Waals and I'm sure you remember him because a name as long and interesting as that shouldn't be forgotten easily. I'll juggle your memory. He was the one who discovered the weak Van der waals forces that hold atoms together. Now let's move on to his other preoccupation.

The ideal gas equation that we have discussed is given as;

$$PV = nRT$$

Van der Waals had observed that the actual volume occupied by a real gas is the molar volume of the gas short of the volume occupied by a mole of its molecules. The 'V' in the equation therefore became 'V$_m$ -b'.

He also noticed that while the molecules of ideal gases were said to not attract each other or interact, real gas molecules did in fact undergo interactions. This implied that they were more easily compressible than ideal gases. He needed to account for this intermolecular attraction and so added 'a/V_m^2' to the pressure of the ideal gas, a constant that alters on account of what gas is being considered. The interaction between real gas molecules lowers the resultant pressure of the gas. These modifications gave rise to the Van der Waals equation shown below:

$$\left(P + \frac{a}{V_m^2}\right)(V_m - b) = RT$$

P = Pressure

a, b = Proportionality constants

V_m = Molar volume

R = Universal gas constant

T = Temperature

For n particles the equation becomes;

$$\left(P + \frac{an}{V_m^2}\right)(V_m - nb) = RT$$

This seems like the perfect time for a break and a soft drink. Just remember Henry's law while you open the can. When you return we would learn how ideal gases differ from real gases and attempt a few questions.

Differences between real gases and ideal gases

Welcome back! I'm sure you had a splendid time watching as the atmospheric and contained CO_2 approached equilibrium, ridding your drink of the fizz. If you didn't then you must have been really thirsty.

We have established that ideal gasses differ from real gases and now we are going to state what those differences are in the table below.

Real Gases	Ideal Gases
1. Real gases have a defined volume.	Ideal gases do not have a defined volume.
2. They have relatively low pressure.	They have higher pressures relative to real gases.
3. Their molecules undergo interaction with neighboring molecules.	Their molecules do not interact with each other.
4. Collision between molecules is non elastic (there is a loss of energy from collisions).	Molecular collisions are elastic (no loss of energy occurs).

5. Intermolecular attraction and repulsion between molecules occur.	No intermolecular forces of attraction and repulsion exist.
6. Real gases exist.	Ideal gases are hypothetical abstractions.
7. They obey Van der Waal's equation of state.	They obey the ideal gas equation.

Table 2. Differences between real gases and ideal gases.

EXAMPLES

1. 0.5dm³ of a gas has a pressure of 700 mmHg. What is its volume in cm³ if the pressure rises to 750 mmHg at a constant temperature?

Solution

Using the Boyle-Marotte formula;

$$P_1V_1 = P_2V_2, \quad T \text{ constant}$$

$$V_1 = 0.5\text{dm}^3$$
$$P_1 = 700 \text{ mmHg}$$
$$P_2 = 750 \text{ mmHg}$$
$$V_2 = ?$$

Now we find V_2 by making it the subject of the formula:

$$V_2 = \frac{P_1V_1}{P_2}$$

$$V_2 = \frac{700mmHg \times 0.5dm^3}{750mmHg}$$

$$V_2 = 0.47dm^3$$

If you stopped here this would be correct, but remember that you were asked to find the volume in cm³.

$$1dm^3 = 1000cm^3$$
$$0.47dm^3 = x$$
$$\therefore x = 1000cm^3 \times 0.47dm^3$$
$$= 470cm^3$$

V_2 is therefore 470cm³.

2. What would be the new temperature of a gas that occupies 0.7dm³ if its initial volume and temperature are 1.2dm³ and 30°C respectively?

Solution

It is important to note that the standard unit for temperature is the Kelvin. When asked a question regarding the temperature of a system it is always good practice to use the Kelvin temperature scale.

Applying Charles' law;

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$$V_1 = 1.2\text{dm}^3$$

$$V_2 = 0.7\text{dm}^3$$

$$T_1 = 30°C$$

$$T_2 = ?$$

Now we find T_2 by making it the subject of the formula:

$$T_2 = \frac{T_1 V_2}{V_1}$$

$$T_2 = \frac{30°C \times 0.7 dm^3}{1.2 dm^3}$$

$$T_2 = 17.5°C$$

Remember that you should always convert to Kelvin.

$$T(K) = T(°C) + 273.15$$

$$T(K) = 17.5 + 273.15$$

$$T(K) = 290.65$$

$$T_2 = 290.65K$$

You could make the temperature conversions before solving for the new temperature. It all depends on what you are comfortable with.

3. 0.5 moles is found in 150cm³ of gas x. How many moles would be obtained in 80cm³ of the same gas?

Solution

Applying Avogadro's law;

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

$$V_1 = 150\text{cm}^3$$

$$V_2 = 80\text{cm}^3$$

$$n_1 = 0.5 \text{ moles}$$

$$n_2 = ?$$

Now we find n_2 by making it the subject of the formula:

$$n_2 = \frac{n_1 V_2}{V_1}$$

$$n_2 = \frac{0.5\text{mols} \times 80 cm^3}{150 cm^3}$$

$$n_2 = 0.2667 mols$$

$$\sim 0.27 mols$$

Remember that you could always convert the volumes to dm³. If we had done that it would have yielded the same result.

4. Calculate the pressure exerted by 0.62 moles of a gas that occupies a volume of 2.5dm³ at 17°C.

Solution

Harnessing the ideal gas law;

PV = nRT

n= 0.62 moles

T= 17°C

Remember to convert to Kelvin:

$$T(K) = T(°C) + 273.15$$
$$T(K) = 17 + 273.15$$
$$= 290.15K$$

V= 2.5dm³

P= ?

R = 0.082 atm dm³ K^{-1} mol^{-1} *(Remember that R is the molar gas constant. It is always this value as long as the units correspond. What this means is that the standard units shown with the value '0.082' must be used in calculations).*

Now we find P by making it the subject of the formula:

$$P = \frac{nRT}{V}$$

$$P = \frac{0.62 mols \times 0.082 atm\ dm3K^{-1}mol^{-1} \times 290.15K}{2.5dm^3}$$

$$P = 5.900\ atm$$

$$\sim 5.9\ atm$$

You are probably wondering why we used the 'atm' unit for pressure and not the usual 'mmHg' that you've been seeing. If we had used it, our calculations would have been flawed since atm is the unit found in the molar constant..

5. Oxygen gas of volume 300cm³ diffuses through an aperture in 35 seconds. Under constant conditions 520 cm³ of an unknown gas G with a vapour density of 64 diffuses through the same orifice. How long would it take G to diffuse?

Solution

Here we use Graham's law.

$$\frac{R_1}{R_2} = \sqrt{\frac{\rho_2}{\rho_1}}$$

$$R_1 = \ ?$$

$$R_2 = \frac{300cm^3}{35s} = 8.57\,cm^3 s^{-1} \qquad \text{(the rate of diffusion of oxygen)}$$

We can obtain the vapour density of oxygen by remembering the formula:

$$2 \times V.D = Relative\ molecular\ mass\ of\ the\ gas$$

$$\rho = V.D$$

$$2\rho = 16$$

$$\rho = \frac{16}{2} = 8.$$

The vapour density of oxygen is therefore 8.

$$\rho_2 = 8$$

$$\rho_1 = 512$$

Substituting the values into the equation;

$$\frac{R_1}{8.57} = \sqrt{\frac{8}{512}}$$

$$\frac{R_1}{8.57} = \sqrt{\frac{1}{64}}$$

$$\frac{R_1}{8.57} = \frac{1}{8}$$

$$R_1 = \frac{8.57}{8}$$

$$R_1 = 1.07$$

*We are required to find out **how long** which means we need to know how many seconds it took G to diffuse. Since;*

$$Rate = \frac{Volume \ of \ gas}{Time \ taken \ to \ diffuse}$$

$$1.07 = \frac{520}{x}$$

Where x is the number of seconds it takes to diffuse.

$$x = \frac{520}{1.07}$$

$$x = 485.98 \ seconds$$

Wow. That's a relatively slow moving gas.

6. At a constant temperature of 25°C a certain gas has a solubility of 0.492 g/L in water at conditions of standard pressure. If the pressure above the surface of the solution rises to 3.7 atm what would its solubility be?

Solution

This problem has Henry's law written all over it.

$$C = k_H \times P$$

$$K_H = \frac{C}{P}$$

$$\frac{C_1}{P_1} = \frac{C_2}{P_2}$$

C_1 = 0.492 g/L

P_1 = 1.0 atm

P_2 = 3.7 atm

C_2= ?

Now we find C_2 by making it the subject of the formula:

$$C_2 = \frac{C_1 P_2}{P_1}$$

$$C_2 = \frac{0.492 gL^{-1} \times 3.7 \ atm}{1.0 \ atm}$$

$$C_2 = 1.82 \ gL^{-1}$$

7. 10 moles of CO_2 occupies a volume of 0.66 L at 289K and 50 atm. Calculate its pressure using Van der Waals equation. (for CO_2, a = 3.61 L^2atm mol^{-2} and b = 0.0428 L mol^{-1}.

Solution

$$\left(P + \frac{an}{V^2}\right)(V - nb) = RT$$

V = 0.66 L

n= 10 moles

T = 289K

R = 0.082 L atm K^{-1} mol^{-1}?

a = 3.61 L^{2}atm mol^{-2}

b =0.0428 L mol^{-1}

P = ?

Now we find P by making it the subject of the formula:

$$P + \frac{an}{V^2} = \frac{RT}{V - nb}$$

$$P = \frac{RT}{V - nb} - \frac{an}{V^2}$$

$$P = \frac{0.082 \times 289}{(0.66 - 10 \times 0.0428)} - \frac{3.61 \times 10}{0.66^2}$$

$$P = 19.352 \; atm$$

$$\sim 19.4 \; atm$$

SUMMARY

- Matter is anything that has weight and occupies space.

- There are five states of matter. These are solids, liquids, gases, plasma and the Bore-Einstein condensate.

- All the states of matter can be converted from one state to another via processes such as evaporation, boiling, condensation, freezing and melting.

- Vapour pressure is defined as the pressure exerted by the vapour of a liquid on the walls of a containing vessel over the surface of the liquid.

- Gases and plasma show a number of differences.

- There are five postulates of the kinetic theory of gases. They show the behavior of an ideal gas. Real gases deviate from these.

- The Boyle-Marotte law states that the volume of a given mass of gas at constant temperature is inversely proportional to its pressure. It can also be shown mathematically as: $P_1V_1 = P_2V_2$..

- Charles' law states that the volume of a given mass of gas is directly proportional to its temperature in Kelvin, as long as the pressure remains constant. It is written mathematically as Mathematically $V_1/T_1 = V_2/T_2$.

- The Kelvin scale is a temperature scale in which the absolute zero is taken to be its starting point (0K) and is equivalent to -273.15 °C.

- $T(K) = T(°C) + 273.15$; is the equation for the conversion between Celsius and Kelvin temperature scales.

- The Pressure Law (or Amonton's law) states that the pressure of a given mass of gas is directly proportional to its temperature in Kelvin, provided the volume is kept at a constant. Mathematically it is $P_1/T_1 = P_2/T_2$.

- Avogadro's law states that equal volumes of all gases at the same temperature and pressure contain the same number of entities or units. It is $V_1/n_1 = V_2/n_2$.

- The ideal gas law states that the volume of a given mass of gas is directly proportional to the number of moles it contains and its temperature in Kelvin but inversely proportional to its pressure. It can be stated as $PV = nRT$.

- Gay-Lussac's law of combining volumes states that when gases react they do so in simple whole number ratios to each other and to their products as long as temperature and pressure remain constant.

- Dalton's law of partial pressures states that the total pressure exerted by a mixture of gasses that do not react with each other can be gotten by adding the individual pressures of the individual gases that make up the mixture.Mathematically for a mixture of n gases;P_{total}= P_1 + P_2 + P_3 + P_4 + P_5… + P_n.

- The Vapour density of a gas is defined as how heavy a certain volume of a gas is in relation to the same volume of hydrogen under the same conditions of temperature and pressure.

- Graham's law states that the rate of effusion (or diffusion) of a gas is inversely proportional to the square root of its relative molecular mass(or vapour density) provided temperature and pressure are kept constant.

- Henry's law states that the amount of a gas dissolved in a liquid is directly proportional to the partial pressure of the gas above the liquid at a constant temperature. This is stated as C = K_H × P.

- Amagat's law of partial volumes states that the total volume exerted by a mixture of gasses that do not react with each other can be gotten by adding the individual volumes of the individual gases that make up the mixture provided temperature and pressure remain constant.Mathematically for a mixture of n gases;V_{total}= V_1 + V_2 + V_3 + V_4 + V_5… + V_n.

- Van der Waal's equation of state describes the properties of a real gas.

- Real and ideal gases are different in a number of ways.

MNEMONICS

You know the drill. Think up some crazy, easy to remember mnemonics. Make it personal if you like. That's even better. I'll try one here.

- The states of matter:

<div align="center">

B   S   L   G   P

</div>

B – Bose-Einstein Condensate

S- Solid:

L- Liquid

G - Gas

P- Plasma

Have you come up with any ones? How about just 'Big Stupid Lizards Get Paid'? or maybe 'Bose Stole Linda's Great Plasma (TV)' ? The choice is yours.

REVISION QUESTIONS

1. a) Define matter.

    b) List and briefly explain the five states of matter.

    c) Describe the process by which water changes state from solid to liquid to gas.

    d) State four differences between gases and plasma.

    e) What is vapour pressure?

2. a) State the five postulates of the kinetic theory of gases.

    b) How many of these postulates apply to real gases? List them.

3. State the following laws and give their mathematical statements if available.

      i.   Charles' law

      ii.   Henry's law

      iii.   The Boyle-Marotte law

      iv.   Avogadro's law

      v.   Gay Lussac's law

      vi.   Amonton's law

      vii.   Graham's law

      viii. Dalton's law of partial pressures

      ix.   Amagat's law of partial volumes

      x.   The ideal gas law

      xi.   Hund's law

4. Using mathematical deliberations show the relationship between the vapour density and relative molecular mass of a gas.

5. State 7 differences between real and ideal gases.

6.   A certain gas has a solubility of 0.3 g/L in water at a pressure of 5.2 atm. If the pressure above the surface of the solution falls to 4.5 atm what would its solubility be?

7. 6 moles of Helium gas has a pressure of 48 atm at 292K. Calculate the volume it occupies using;

    a) Van der Waals' equation.

    b) The ideal gas equation. (for He, a = 0.0341 L^2atm mol^{-2} and b = 0.0237 L mol^{-1}).

8. Hydrogen gas of volume 150 cm^3 diffuses through an aperture in 42 seconds. Under constant conditions 300 cm^3 of an unknown gas G with a

vapour density of 60 diffuses through the same orifice. Oche, a playful chemist bets some money on X traveling faster than hydrogen. How long would it take X to diffuse? Would Oche lose his money?

9. In order to achieve the complete combustion of 150cm^3 of pentane (C_5H_{12}) what volume of oxygen would be required?

10. Calculate the volume of dry hydrogen gas collected at s.t.p when a volume of 80cm^3 of the gas is collected over water at a temperature of 30°C and a pressure of 790 mmHg. (The S.V.P of water at 30°C is 31.80 mmHg).

CHAPTER 5: REACTIONS
Kinetics and Types

We had briefly introduced the concept of a chemical reaction in chapter 2. There we defined what chemical reactions are and examined a few examples of those. In this chapter we would go a bit further by discussing the different types of reactions that there are as well as their *kinetics.*

"Chemical kinetics is a branch of chemistry that deals with the study of the rates of chemical reactions."

A lot of exciting things occur when a chemical reaction takes place. The atoms of the reactants interact in particular ways that lead to the formation of the products. You see the results of those interactions through color changes, subtle weathering, explosive occurrences and other observations.

Figure 5-1 The reaction between sodium and water is explosive.

Chemical reactions are always happening and are all around us. One does not need to wear special gear to note their occurrence. For instance the process of photosynthesis is a chemical reaction plants undergo that involves the conversion of carbon dioxide and water in the presence of sunlight energy to form the sugar (glucose) and oxygen.

$$6CO_{2(g)} + 6H_2O_{(l)} \rightarrow C_6H_{12}O_{6(s)} + 6O_{2(g)}$$

We would now talk about the different **types of reactions** known to scientists.

Combination (or synthesis) Reactions
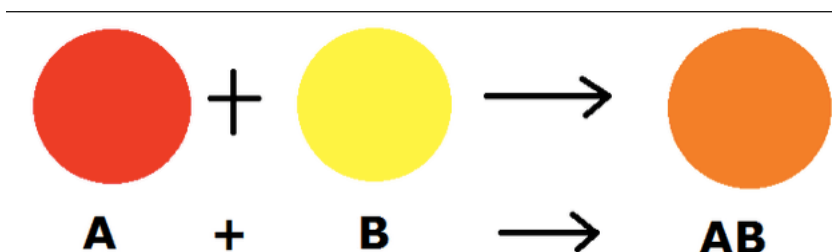
Some reactions involve the coming together of two or more reactants to yield products. This can be intuitively understood as we know by everyday experiences that when two or more things combine, better utility could be obtained. For example imagine having a bicycle with amazing design and body work but just a single tire or worse, no tires at all. I really can't see the point of such a means of transport if you are better off walking. When you add tires however, you find that your bike is more complete and you can enjoy the service it renders. The same goes for combination reactions. The reactants combine to form products. However, whether the products are useful or not is largely dependent on their effects.

"A combination (or synthesis) reaction is a reaction that occurs when two or more reactants come together to form a product."

Combination reactions of different types can occur depending on what and what come together to produce something. The general form of a combination reaction is shown below:
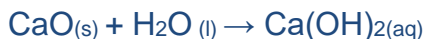
$$A + B \rightarrow AB$$

A is the first reactant, B is the second reactant and AB is the product formed when they react.

When two elements come together, they yield compounds.

$$2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(l)}$$
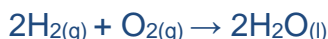
Compounds can also equally combine to form other much bigger compounds.

$$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2(aq)}$$

Sometimes an element and a compound may combine.

$$2CO_{(g)} + O_{2(g)} \rightarrow 2CO_{2(g)}$$

These are only a few examples of the kinds of combination reactions that occur. We would continue to examine them as we move on in the discussion.

It is important to note that just like me and good sleep, the combination of certain substances just do not work out and reactions never occur with them. An example is one you can do at home. You can try pouring all the oil in the world into a bowl of water but you'll never get the two constituents to do anything but separate. The reason why some substances react and others do not would be explored soon.

Decomposition Reactions

$$AB \rightarrow A + B$$
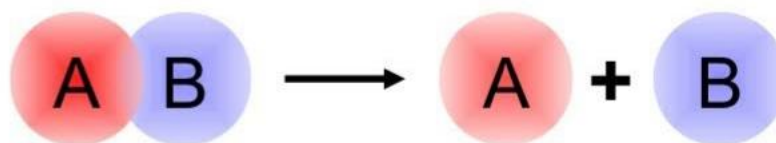
While in combination reactions we spoke about adding substances together, in decomposition reactions we talk of breaking them down. Some compounds can be reduced into simpler forms. If your awesome bike got a bit old and you being such a crafty wiz decide you could use the individual parts instead, when you take your bike apart you are doing something analogous to a decomposition reaction.

"A decomposition reaction involves the breakdown of a compound into two or more simpler forms."

The general form of a decomposition reaction is shown below.

$$AB \rightarrow A + B$$

Decomposition reactions are prevalent in the industrial sector. For instance they are used in car airbags; you know the puffy bag that shoots out from the steering wheel when you or someone else is being a little too naughty or is a victim of an unfortunate collision. The bags emerge due to the breakdown of a compound known as sodium azide [(NaN$_3$)$_2$] that on decomposing due to an impact produces Sodium (Na) and Nitrogen gas (N$_2$) which make the bag puff up like that.

When some sources mention decomposition reactions they tend to present them as thermal decomposition reactions. That is however just one type of decomposition. You are probably wondering why there are so many 'types of types of types' but things can occur in more than one way and decomposition is just one of those things. The three **types of decomposition** reactions are:

1. **Thermal decomposition reaction:** This type of decomposition involves the application of heat. When the substance is heated it breaks down, forming simpler substances. It is also termed **thermolysis.**

$$CaCO_{3(s)} \xrightarrow{heat} CaO_{(s)} + CO_{2(g)}$$
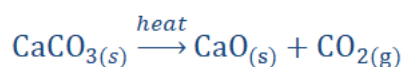
2. **Electrolytic decomposition reaction:** Here, an electric current is introduced and as it passes through an aqueous solution of a compound it breaks it down and forms simpler elements. Water can be decomposed in this way to form hydrogen and oxygen.

$$2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)}$$
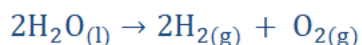
3. **Photolytic decomposition reaction:** In this reaction, light is the weapon of decomposition here. More complex substances or compounds on exposure to light are broken down to form simpler elements. The breakdown of silver bromide molecules (AgBr) when exposed to sunlight is a perfect example of a photolytic decomposition reaction. Here the decomposition is observed on account of a change in color of the AgBr crystals from light yellow to a grayish color.

$$2AgBr_{(s)} \xrightarrow{sunlight} 2Ag_{(s)} + Br_{2(g)}$$
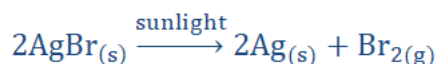
Catalytic Reactions

When I was in secondary school I had a classmate who I would call…Anno Yihin (just a coincidence that it sounds like 'annoying'). Anno Yihin was disliked by

most people because he had the habit of starting fights between good friends and then slyly disappearing from the scene so that nobody thought to mention him when an attempt was made to settle the quarrel. He also never seemed to be bothered by his actions. He could *cause* fights but was himself *unaffected* by the situation. Catalysts are just like Anno except their intrusions may be welcome sometimes. They can affect chemical reactions by making them go fast or slow but are themselves not involved in the reaction. A catalytic reaction is therefore a reaction that includes catalysts to aid product formation. It is also termed **catalysis.**

"A catalytic reaction is one that involves the use of catalysts to aid in the formation of products."

"Catalysts are substances that alter the rates of chemical reactions but are themselves chemically and quantitatively unchanged when the reactions conclude."

Just like Anno, catalysts can either speed up or slow down reactions but are more or less unaffected by the reaction. Their chemical and quantitative compositions do not alter.
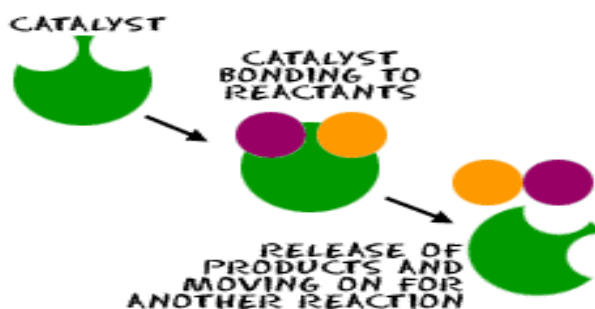

Figure 5-2 Catalysts remain unchanged at the end of a reaction.

Catalytic reactions are of two types depending on the states of the participating substances.

1. **Homogeneous catalytic reaction:**

   In this reaction type all the participating substances are of the same state as the catalyst. What this means is that each reactant, product and the catalyst must be liquid, gas or solid.

   $$C_2H_{4(g)} + H_{2(g)} \xrightarrow{Pd/C(g)} C_2H_{6(g)}$$
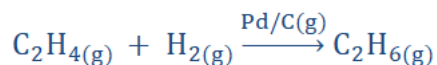
   The reaction shown above is the *hydrogenation of ethene* and as you may observe, all participating substances are in the gaseous form. Don't worry your head about the process of hydrogenation yet as we would soon get to that. For now, be content with understanding the concept of homogenous catalysis.

2. **Heterogeneous catalytic reaction:**

   Catalysis of this nature is the opposite of homogeneous catalysis. Here, the different participating substances are in different phases from the phase of the catalyst.

   $$N_{2(g)} + 3H_{2(g)} \xrightarrow{Fe(s)} 2NH_{3(g)}$$
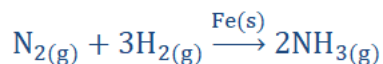
   While catalytic reactions are of two types as seen above, **catalysts** are also of a number of types. Some catalysts occur naturally and are hence called **organic** catalysts while those synthesized in the laboratory are **inorganic** catalysts.

1. **Organic catalysts:**

   These catalysts are involved in **organocatalysis** which is just a type of catalysis consisting of an organic catalyst. They typically consist of carbon, sulfur and hydrogen-elements found in organic compounds. A well known example of an organic catalyst is an enzyme. Enzymes are biological catalysts that affect the rates of reactions that occur in the bodies of organisms.

2. **Inorganic catalysts:**

   These catalysts are usually synthesized in the laboratory as opposed to being made in the bodies of living creatures. They are divided into two types; **positive** and **negative catalysts.**

Positive catalysts are inorganic catalysts that help to speed up the rate at which a chemical reaction is going. Good examples of positive catalysts are potassium permanganate ($KMnO_4$) and Manganese dioxide (MnO_2). These catalysts are used in a host of industrial processes such as in the making of pesticides, air treatment and automotive care.

Negative catalysts on the other hand retard the rates of chemical reactions. Examples are phosphoric acid (H_3PO_4) and Tetra Ethyl Lead (T.E.L).

It is important to know that catalysts themselves can be affected by the addition of another substance. They can be made to be more efficient or have their tendency for speed dampened. Substances that improve the efficiency of a catalyst by making it speed up a reaction even more are known as a **promoters** or **accelerators.** Those that do just the opposite, reducing the efficiency of a catalyst are **inhibitors.**

When I learnt about catalysis for the first time, I couldn't wrap my head around why promoters and inhibitors weren't catalysts themselves. It just made a whole lot of sense that they could be called catalysts not just because I wanted to memorize fewer names but because they seemed to do the same thing catalysts do. Took me a while to realize that while catalysts are concerned with the reaction itself, promoters and inhibitors are concerned with the catalysts and so they have little to no bearing or effect on the reaction.

Thermal dissociation reaction

I can see into the near future. I got that ability from staying awake so long that things got a little strange. My 'that's so Raven' inspired senses are telling me that you may get a little confused in a while. But don't worry. We'll get through it.

Not long ago we spoke of thermal decomposition. We defined it as the breakdown of a compound or larger entity into simpler substances on account of the application of heat. Now we would be talking of another process similar to the breaking down of a compound due to heat but different in a few ways.

"Thermal dissociation reaction is a reaction that involves the splitting of a compound or more complex entity into its simpler compositions."

Yes, I know. It does sound like a lot like decomposition but it really isn't. Picture this. Imagine I give you and Anno Yihin (yes, he's back) sheets of paper that are my very important credentials and ask both of you to ruin them in such a way that I could fix them again. You decide to only tear the sheets of paper in half, aware that you could put them back together with some glue. Anno on the other hand being such a peaceful young man decides he would do the same, however he doesn't stop there. He decides to crumple the papers, chew them and then stomp on them after which he places them in a bowl of water and makes 'credential soup'. He undergoes so many stages of destruction as though he were a positive catalyst. As you can probably see your papers can return to their initial states with just some glue but his can't. Your actions with the papers are *reversible* but for Anno there are *irreversible.* He can never get the papers back the same way. He can probably also never get his bones back the same way if someone breaks them.

The same reasoning applies for decomposition and dissociation reactions. Decomposition reactions are largely irreversible and are mostly naturally occurring. Dissociation reactions on the other hand are reversible. After the products are formed, they can revert to the reactants again.

Thermal dissociation reactions are of the form;

$$AB \overset{\text{heat}}{\longleftrightarrow} A + B$$
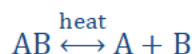
As you can see above the arrow points in both directions meaning that the reaction can go in both ways under the right conditions (right conditions of temperature and pressure). Some examples of thermal dissociation reactions are;

$$N_2O_{4(g)} \rightleftharpoons 2NO_{2(g)}$$
$$Cl_{2(g)} \rightleftharpoons 2Cl_{(g)}$$
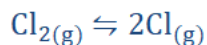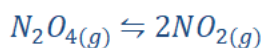
Reversible reactions

Many of the reactions we have considered before now have been **irreversible reactions.** They have only proceeded in one way.

$$A + B \rightarrow C + D$$

Reversible reactions occur in both directions. Thermal dissociation is one instance of a reversible reaction as we have just seen. Reversible reactions must not require heat to occur. All reactions that can be reversed irrespective of the means used to do this are reversible reactions. They are usually of the form;

$$A + B \leftrightharpoons C + D$$
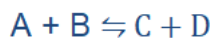
It is fascinating to note that for as long as possible chemists had believed that all reactions could only proceed in one way. It took some out of the box thinking for Claude Louis Berthollet who proved this wrong in 1803.

Reversible reactions may only occur under certain conditions such as at specific temperatures and pressures. They are particularly interesting because the formation of products and the reverse (formation of reactants) can take place simultaneously when the conditions required both for product and reactant formation are similar. What this implies is that the process may be ongoing until *equilibrium* is met. Equilibrum happens when the amount of products formed balances the reactants reformed and the process can then be brought to a stop. It's like having Anno and someone you find displeasing engage in exchanging blows until both of them tire out and maybe get concoctions. Their hits were reversible until there was balance in the form of their double concoction.
Some examples of reversible reactions are:

$$2NaCl_{(s)} + CaCO_{3(s)} \leftrightharpoons Na_2CO_{3(s)} + CaCl_{2(s)}$$
$$NH_4Cl_{(s)} \leftrightharpoons NH_{3(g)} + HCl_{(g)}$$
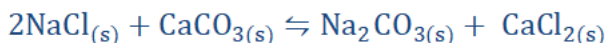
Displacement reactions

Just as the name implies, a displacement reaction is one concerned with replacing some participating entities (atoms, molecules, elements) in a reaction with other participating entities.

"A displacement reaction is one in which one or more atoms of an element displace another/others in a compound."
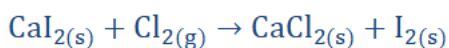
Displacement reactions are of the form;

$$A + BC \rightarrow AC + B$$
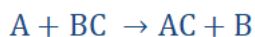
There are of two types. These are *single (substitution) displacement reactions* and *double (metathesis) displacement reactions.*

Single (substitution) displacement reaction:

This reaction involves the replacement of only one atom of an element in a compound by another.

$$CaI_{2(s)} + Cl_{2(g)} \rightarrow CaCl_{2(s)} + I_{2(s)}$$

The I_2 in CaI_2 on the reactant side was replaced by Cl_2 leading to the formation of $CaCl_2$ and the displacement of I_2. An amusing way to visualize a single displacement reaction is to imagine that a loved one bought you a new pet. I can picture you dancing around with your pet puppy all over the place. But then one day our 'friend' Anno shows up at your door and takes the pet forcefully from you because he has something you don't, maybe special puppy food and you are left alone, seemingly replaced by Anno. Sounds sad, but it satisfies our aim of explaining what a single displacement reaction is.

Another way to picture it is to imagine going to a school dance with your friends. Your friend Tunde comes with his date and is having a good time showing off his moves when suddenly Anno shows up and is surprisingly a better dancer, winning Tunde's date over with his moves. Tunde is left alone. Hopefully he won't let that stop his dancing. He should also probably find a better date next time.

Figure 5-3

Double (metathesis) displacement reaction:

Here two atoms are being exchanged, forming two new compounds as opposed to one.

$$KI_{(aq)} + Pb(NO_3)_{2(aq)} \rightarrow KNO_{3(aq)} + PbI_{2(s)}$$
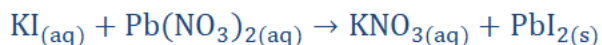
We can see from the equation that the compounds seem to undergo some sort of exchange. Potassium (K) accepts the nitrate (NO_3) from lead (Pb) and lead (Pb) receives iodine (I) from Potassium (K).

Let's imagine that a friend of yours Chika sees what happened to Tunde and decides to dance with him. At that moment the teachers chaperoning the dance decide to be involved because it seems the 'cool' thing to do (gulp). As Tunde dances along and gets into the music he switches partners and notices that he now dances with his biology teacher Mrs. Biohr Logia (awkward) while the Economics teacher Mr. Ecoo Nomica gives Chika a twirl. Well, things seem to be getting out of hand but the important thing here is that a double displacement has taken place. Tunde and Chika switched dance partners with Mr. Ecoo Nomica and Mrs. Biohr Logica on the dance floor. You could also join in on the dance floor and see what reactions you may partake in.
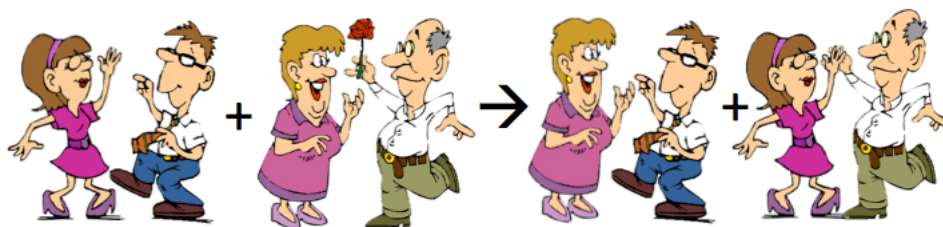
Double Displacement

Figure 5-4

It is easier to think of single displacement reactions in terms of a **replacement** while double displacement reactions seem more of an **exchange.**

Combustion reaction

Any reaction that involves the evolution of heat and typically involves burning in oxygen is a combustion reaction. Oxidants are substances that can induce combustion in other substances. Oxygen is regarded as a significant oxidant but other substances such as fluorine are oxidants as well. The release of heat that occurs in a combustion reaction is usually accompanied by light. A *combustible*

substance that is capable of burning in an oxidant as is composed of combustible substances is known as a *fuel.* These reactions have the form:

$$Fuel + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(l)}$$
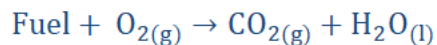
Combustion reactions are very common. If you light a candle, burn some firewood or anything that burns you have witnessed a combustion reaction. My most memorable experiences when going to the village for Christmas always involved the smell of burning firewood in the cold mornings. I loved to experience this because I could tell the chemistry of the process and that was thrilling. The reaction below is an equation roughly showing the combustion of wood (cellulose) as it is a multi-step process in reality.
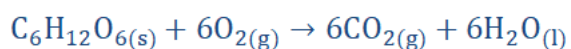
$$C_6H_{12}O_{6(s)} + 6O_{2(g)} \rightarrow 6CO_{2(g)} + 6H_2O_{(l)}$$

Figure 5-5 Combustion reactions are not always as adorable as small Christmas time fires. The smoke we observe when we burn something is usually a gas mixture that is the product of the reaction. Smoke produced from incomplete combustion tends to contain unburned particles of the fuel; that we see however when a complete combustion reaction takes place, H_2O and CO_2 become the only products. Some examples of combustion reactions are shown below;

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$$
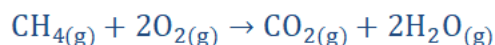
In the above we see the combustion of methane, a hydrocarbon.

$$C_5H_{12(g)} + 8O_{2(g)} \rightarrow 5CO_{2(g)} + 6H_2O_{(g)}$$
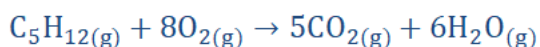
Here we have the combustion of pentane which is another hydrocarbon. No, I'm not speaking Spanish (I wish), it's just chemistry. We'll find out about hydrocarbons in time.
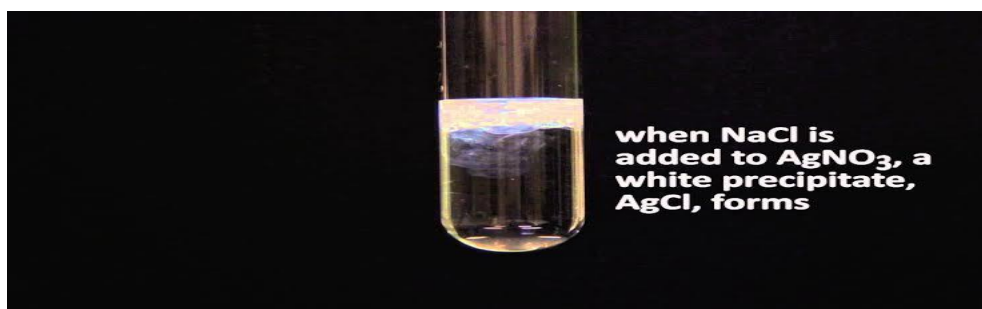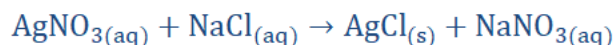
Precipitation reaction

Figure 5-6 Precipitation reaction

Every time I insist you get a drink before continuing our little discussion I get one for myself as well. I like the taste of lemons so I get a sachet of lemon tea. I really enjoy drinking it but it has one problem; in hot water the contents of the sweet lemon tea dissolve easily, but when I put it in cold water they don't. They just float around in clumps. This is quite frustrating especially since I enjoy and need cold drinks to cool my head down after all this chemistry. Precipitation reactions are similar to my cup of cold lemon tea. When reactants react, they form products and one of those products is usually insoluble in solution and would just float around or *precipitate* out of the solution. The liquid left behind in the formation of a precipitate is a *supernate.*

"A precipitation reaction is defined as one that involves the reaction between two soluble reactants in an aqueous solution to form products; one of which is insoluble."

Precipitations can also be defined in terms of the reaction between cations and anions in aqueous solutions to yield ionic solids that are insoluble. An example of a precipitation reaction is shown below;

$$AgNO_{3(aq)} + NaCl_{(aq)} \rightarrow AgCl_{(s)} + NaNO_{3(aq)}$$

If you are keen- and I can tell you are- You would probably be saying something now in the lines of; "Hey! That's double displacement!" and of course I have some explaining to do.

Just like thermal dissociation was a kind of reversible reaction, precipitation reactions can be single and double displacement reactions. The only catch here is

that for double displacement reactions to be precipitation reactions there must be the formation of a solid, insoluble product and an aqueous solution. All these conditions are fulfilled by the reaction shown above. Single displacement reactions also become precipitation reactions when one reactant ion is being replaced by another and a new solid product is formed.

It can be difficult to understand these reactions from an ionic perspective. Let's clear up that confusion before moving along.

$$Ag^+_{(aq)} + NO^-_{3(aq)} + Na^+_{(aq)} + Cl^-_{(aq)} \rightarrow Na^+_{(aq)} + NO^-_3 + AgCl_{(s)}$$
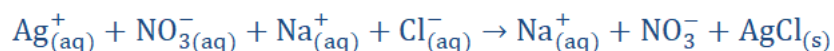
The above is the ionic equation of the reaction stated above. What we are presently doing is trying to arrive at the **net ionic equation** of the reaction. The first thing we have done here is separate the individual ions of the reaction. I am certain you recall what ions are. If you do you would realize that the elements with the superscript '+' are cations; having one to a few electrons on their valence shells to give away. Those with the '- 'superscript are anions and so have to receive electrons to complete their octet shells. When these exchanges take place, the aqueous and solid products are formed. When we cancel out the ions repeated on both sides of the equation (spectator ions) we get;

$$Ag^+_{(aq)} + Cl^-_{(aq)} \rightarrow +AgCl_{(s)}$$
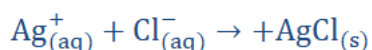
After this I am quite sure the definition of precipitation at the start of this section is now clearer to you. Now imagine if all the participating entities were aqueous meaning that none would be solid. Would you still be able to obtain a precipitate? I'll wait.

Solid-state reaction

Be honest. Before you began studying chemistry and became a bonafide chemist yourself, when you pictured chemists working you always imagined them holding a test tube with some kind of liquid in it, looking studiously at the content of that test tube. Can't count how many Chemistry textbook covers look like that. We seem to always talk about liquids in chemistry that the only times we refer to solids is when we have to do something to them with liquids. This is understandable as liquid molecules are freer and hence much more available to react than solid molecules. Nonetheless reactions between just solids also take place and those reactions are known as solid-state reactions or solid state synthesis.

"Solid state reactions are reactions between solid substances to form products."

Due to the fact that solid substances have a more rigid structure, it is usually necessary to grind the reactants in order to allow for proper mixing and hence a reaction to occur. Some solid state reactions may also only occur under specific conditions such as at very high temperatures. Surface area and reactivity are also factors taken into account when carrying out solid synthesis.

Reduction and oxidation reactions (REDOX)

Chemical reactions can be analogous to passing in a game of basketball. When one player passes the ball, the other player receives it. It'll make no sense for the player catching to intentionally miss the ball, unless he was just a bad basketball player, like I was in my university team. The same thing happens in a reduction and oxidation reaction. One of the reactants gives off an electron that is received by the other reactant. The reaction is therefore divided into two halves; the first is the oxidation reaction and the second is the reduction reaction.

Oxidation is therefore defined as the loss of electrons, while reduction is defined as the gain of electrons. Saying 'reduction and oxidation' takes a lot so we would call it a redox reaction instead.

"An oxidation-reduction reaction (redox) reaction is defined as the transfer of electrons between reactants to form products."

"Oxidation is defined as the loss of electrons during a chemical reaction."

"Reduction is defined as the gain of electrons during a chemical reaction."

The reactant that is giving its electron(s) away is known as the reducing agent while the reactant accepting the electron(s) is the oxidizing agent. Don't look confused, it takes me back to when I learnt it. I remember how easy it was to mix up the two. If oxidation is the loss of electrons then why is a reducing agent losing the electrons? Let's clear this up.
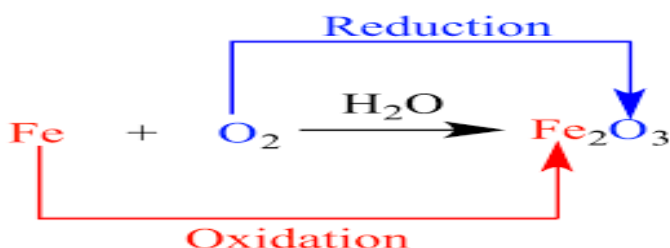

Figure 5-7 Explaining the redox reaction

In the above we find the reaction between iron (Fe) and oxygen (O_2) to form iron(II)oxide. Iron loses electrons and oxygen gains them. Since Fe is losing the electrons it is becoming oxidized. O_2 is gaining the electrons and so is being reduced. Since Fe is being oxidized, it is reducing O_2 so it is the *reducing agent.* O_2 on the other hand is accepting electrons and so is undergoing reduction but at the same time it is oxidizing Fe and so it is the *oxidizing agent.*

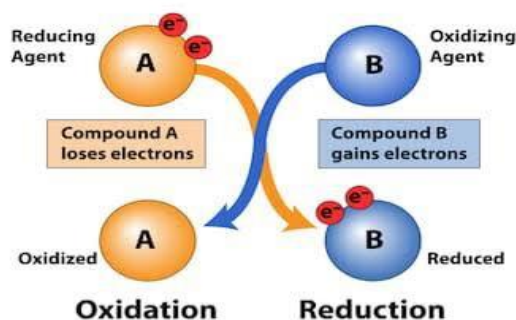**Figure 5-8**

Oxidation states

An element's tendency to lose or gain electrons can be described by considering the oxidation state of that element.

"The oxidation state of an element shows the number of electrons of an atom of the element that

is involved in bond formation with the atom of another element."

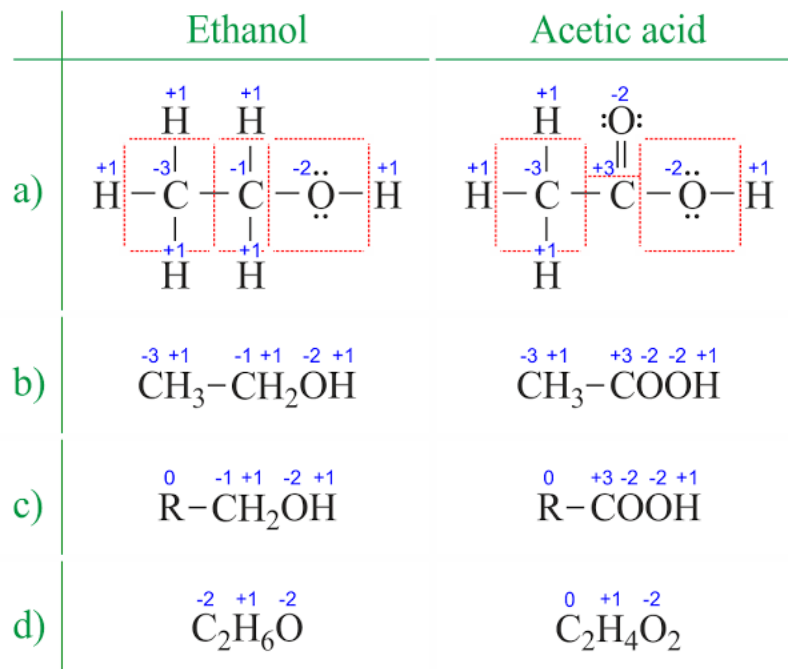The oxidation state of an element can sometimes be referred to as its oxidation number.

Figure 5-9

The above image shows the different ways by which the oxidation states of atoms of elements can be deciphered. Here we have ethanol and acetic acid. In (a) let's find the oxidation state of the first carbon (C). As you can see this C is bonded to 3 H and one other C. Each H contributes one electron to the bond and C contributes one each. For the H-C bonds, we have 6 electrons in total (remember that 1 'dash' signifies 2 electrons). So the first C gains 6 electrons from these bonds. However when we talk about the C-C bond, we do not include 2 electrons but consider just 1 electron. This is because for bonds between atoms of the same type, we divide them equally. The oxidation state of the first C is then gotten by subtracting the bonds (number of electrons) that the C has gained from the number of valence electrons in a C atom. For some elements we would also consider lone pairs of electrons (electrons that do not form bonds but stand alone) but that does not apply in this case as all four valence electrons of C are involved in bond formation. We can use an equation to represent this;

Oxidation state of atom of element

$$= \text{Number of valence electrons} - \text{Sum of bonding and lone electrons}$$

We may not always be able to spread up a compound like that to notice what bonds with what and so in order to know the oxidation state of an element relatively easily we follow a set of arbitrary rules. These **rules for assigning oxidation numbers** are;

1) The oxidation states of *free* elements such as O_2, N_2 and so on are assigned an oxidation number of 0. Free states are when elements are stable and largely unreactive in that state. O_2 for instance is diatomic in the free state.

2) The oxidation number of H_2 is +1 unless it is found in compounds that have elements less electronegative than it is. In that case it becomes -1.

3) Oxygen usually has an oxidation number of -2. This could change however on account of the extent of electronegativity of the elements it can be found with in a compound.

4) In writing a formula, the cation should be written first before the anion. An interesting example can be found in the compounds NaH and HCl. The oxidation number of H in HCl is +1 and so being the cation it is written first. However in NaH, the oxidation number of H is -1 and so H being anionic comes after Na.

5) The charge on an ion is not the same thing as its oxidation number. Though in the case of monoatomic ions this is so. The oxidation state of Na for example is +1 (Na^+).

6) The oxidation number of a neutral compound is 0, implying that the sum of the oxidation numbers of the atoms in a neutral compound is 0.

7) For polyatomic ions, the oxidation numbers equal the charges on the ion. For instance for NO_3^{-1} the oxidation number is -1.

The concept of oxidation numbers can be a difficult one to wrap your head around. In fact since the beginning of this section, redox reactions have given us nothing but trouble. But just take a deep breath and read through it a few more times and it would become clearer to understand. And of course, I'll help. Have a look at the compound below;

$$Na_2SO_4$$
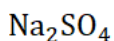
Imagine you are asked to give the oxidation number of S in the formula how would you go about it? I'm quite sure you suggested that we follow the oxidation numbering rules. Let's do just that.

First we note the oxidation state of Na which is +1 in accordance with number 5 of the rules; as it is a monoatomic ion with a charge of +1 (remember?). As for oxygen its oxidation number is -2 following number 3 of our 'oxidation number' seven commandments. So it seems the only oxidation number that eludes us is the one for sulfur (S) but that isn't a problem. Recall that he oxidation number of a neutral compound is 0 and Na_2SO_4 is a neutral compound. Now all we have to do is try to make the resultant oxidation number 0.

If Na is +1 and O is -2 and we have 2 Na atoms and 4 O atoms, we simply each charge by the number of electrons and then add them together to obtain 0.

$$Na_2SO_4 = 0$$
$$(+1 \times 2) + S + (-2 \times 4) = 0$$
$$2 + S + (-8) = 0$$
$$2 + S - 8 = 0$$
$$S = 0 + 8 - 2$$
$$S = +6$$

Let's see if this is accurate by adding all the charges and seeing if it equals 0.

$$Na_2SO_4 = 0$$
$$(+1 \times 2) + (+6) + (-2 \times 4) = 0$$
$$2 + 6 + (-8) = 0$$
$$2 + 6 - 8 = 0$$
$$8 - 8 = 0$$

Since Na_2SO_4 is a neutral compound and the oxidation numbers add up to 0, we know for certain that the oxidation number of S in the compound is 0.

Understanding redox reactions in the scope of oxidation numbers

Now that we are fairly certain we get the gist of oxidation numbers, we can go on to applying the idea to redox reactions. Have a look at the equation below.

$$Fe_{(s)} + O_{2(g)} \rightarrow Fe_2O_{3(g)}$$
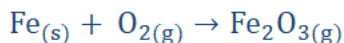
Since oxidation is the loss of electrons and reduction the gain of those electrons, one of these species is losing electrons and the other gaining. We have already established that the reducing agent is giving off electrons while the oxidizing agent is

accepting the electrons. Geared with this knowledge and the oxidation assignment rules, we can now learn how their oxidation numbers change.

Both Fe and O have oxidation states of 0 at the start of the reaction as there are both in the neutral states in accordance with the first law. On reacting however, their oxidation numbers change. We have already learnt that the oxidation state of O in a compound is -2. We should also be aware that Fe_2O_3 is a neutral compound.

$$Fe_2O_3 = 0$$
$$(Fe \times 2) + (-2 \times 3) = 0$$
$$2Fe - 6 = 0$$
$$2Fe = 6$$
$$Fe = \frac{6}{2}$$
$$Fe = +3$$

If you input this value in the formula and add them together you would find that it equates 0, showing that it is correct.

So now we see from the equation that the oxidation state of oxygen changed from 0 to -2 while the oxidation state of Iron changed from 0 to +3. O gained electrons and went from being neutral to being a negative ion (anion) while Fe lost electrons going from a neutral atom to a positive ion (cation).

The loss of electrons or oxidation took place when the oxidation state of Fe changed from 0 to +3 while the gain of electrons (reduction) happened when O changed oxidation state from 0 to -2. Since Fe was making O accept electrons it reduced O and so is the reducing agent and since O made Fe give up its electrons it was oxidizing Fe and so is the oxidizing agent. This new information grants us an alternative definition of a redox reaction.

"An oxidation-reduction (redox) reaction is one in which the oxidation number of a specie (atom or molecule) alters by the loss or gain of an electron."

"Oxidation is defined as the increase in oxidation number of a reacting specie during a chemical reaction."

"Reduction is defined as the decrease in oxidation number of a reacting specie during a chemical reaction."

Figure 5-10 The rusting of iron is a common example of a redox reaction. Fe reacts with O_2 to form Fe_2O_3.

Neutralization reaction

When a substance known as an acid reacts with another substance known as a base they form the products salt and water. Such a reaction is a neutralization reaction.

Acids

"An acid is a substance that donates protons (hydrogen ions) on dissolution in water."

This is only just one definition of an acid and it is attributed to Johannes Nicolaus Bronsted and Thomas Martin Lowry. It is therefore appropriately named the **Bronsted-Lowry acid**. They proposed this definition in 1923. Acids have undergone

a number of definitions and are so named depending on the definition. Svante Arrhenius defined an acid as;

"…Any substance that increases the hydronium (or oxonium) ion (H_3O^+) concentration in solution."

And so it is named the **Arrhenius acid**. The hydronium ions referred to here are simply just the outcome of H^+ (hydrogen ions) dissociating from the acid to form bonds with the water. Lastly;

"An acid is a substance that accepts electron pairs."

This was proposed by Gilbert N. Lewis (remember him?) and is the **Lewis acid.**
Acids can be **strong acids** or **weak acids.**

Strong acid: When an acid ionizes or dissociates completely in solution, it is known as a strong acid. Examples of strong acids are HCl, HBr, HI, H_2SO_4, HNO_3, $HClO_4$ and $HClO_3$. There are only about a handful of substances that ionize completely in solution producing hydrogen ions and the seven mentioned here are the only strong acids known which to me is pretty mind blowing. All the other acids besides these you may come across are very likely weak acids.

Weak acids: These are not completely ionized in solution. They dissociate only partially and so can co exist in solution with their *conjugate bases*. Conjugate bases are acids that lose hydrogen ions which are accepted by bases. If the base is a weak base and does not ionize completely it would only partially receive hydrogen ions and hence form a *conjugate acid.* This would be explained briefly.

Acid characteristics

Though the underlying basics for the behavior of an acid is the existence of H^+ in solution, acids can be identified on account of the properties that they possess. These properties are listed below.

1) They turn blue litmus red: Litmus paper is a special kind of paper; special because it has undergone treatment with particular dyes to change color when placed in contact with an acid. When blue litmus paper is dipped in acid, it turns red.

2) They are corrosive and just downright dangerous when concentrated.
3) They have sour tastes: Am almost certain you have tasted an unripe fruit before. Believe it or not you actually tasted a weak acid (usually acetic acid).
4) They have a PH of less than 7: PH is a scale used by chemists to determine whether something is acidic or basic. You would soon come to understand this fully after we talk about bases.
5) They react with bases to form salt and water (neutralization).
6) They generally react with metals to liberate hydrogen gas: This is noted below when nitric acid (HNO_3) reacts with calcium (Ca) to form the salt calcium nitrate [$Ca(NO_3)_2$] with H_2 liberated.

$$2HNO_{3(aq)} + Ca_{(s)} \rightarrow Ca(NO_3)_2 + H_{2(g)}$$
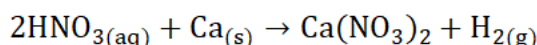
Acids can be classified into **organic acids** and **inorganic (mineral) acids.** The organic acids occur naturally (such as the taste of unripe fruits) while the mineral acids are synthesized in the laboratory.

Bases

You have already seen that bases are the substances that react with acids to form salt and water. They can also be said to be the substances that produce hydroxide ions in solution.

"A base is a substance that increases the hydroxide ion (OH$^-$) concentration in water."

So while acids increase the concentration of hydronium (H_3O^+) ions in water, bases increase hydroxide ions (OH^-). Both ions combined produce a water molecule.

$$H_3O^+ + OH^- \leftrightharpoons H_2O$$
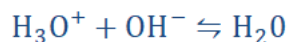
Just like acids bases can be termed **Arrhenius**, **Bronsted-Lowry** and **Lewis** bases with corresponding definitions.

Base characteristics

Just like acids, bases have some specific characteristics. These are;
1) They turn red litmus paper blue.

2) They have a slippery texture.
3) They have a characteristic bitter taste.
4) They have a PH of above 7.
5) They react with acids to form salt and water.
6) They can be either soluble or insoluble in water. Soluble bases are known as **alkalis**.

Bases are divided into strong bases, weak bases, super bases and solid bases.

Strong bases: These are bases that completely ionize in water to produce hydroxide ions (OH^-). There are also known as substances that remove H^+ with ease from weak acids. Remember that H^+ ions are what make substances acidic; when dissolved in water they dissociate to produce those hydrogen ions. However in water the H^+ become H_3O^+. Bases that can remove those hydrogen ions from acids are strong bases and this process is termed the **basicity of an acid**. Note that some acids are more basicity than others, meaning they have more replaceable hydrogen ions in their molecules.

"The basicity of an acid shows how many replaceable hydrogen ions there are in one molecule of the acid."

How many H^+ that can be removed by strong bases can be known from just looking at the formula of the acid. For instance sulphuric acid (H_2SO_4) is **dibasic** since we see two hydrogen ions that can be removed by a strong base ($2H^+$, SO_4^{2-}). For nitric acid (HNO_3) the basicity is 1 and so the acid is monobasic; as one hydrogen ion can be removed by a strong base (H^+, NO_3^-). What do you think would be the basicity for phosphoric acid (H_3PO_4)? I'll wait. An example of a strong base is potassium hydroxide (KOH).

Weak bases: Weak bases only ionize partially in water to produce hydroxide ions and so in solution they tend to exist with their *conjugate acids*. Conjugate acids are formed when a base accepts hydrogen ions from an acid. So a conjugate acid is basically a base with a hydrogen ion added to it. They are only possible when incomplete ionization occurs as in the case of a complete dissociation of a base into OH^- a strong base would occur. To make this easier to understand, note that the weaker the conjugate acid present, the stronger the

base and the weaker the base, the stronger the conjugate acid. One example of a weak base is ammonium hydroxide (NH_4OH).

Super bases: These are strong bases with capes. They are even better at dissociating completely to form bases and removing H^+ from acids. Orthodiethynylbenzenedianion ($C_6H_4(C_2)_2)^{2-}$) is the strongest superbase known. I hope you didn't hurt yourself saying that.

Solid bases: Any base in solid form can be considered a solid base. An example is sodium hydroxide ($NaOH$).
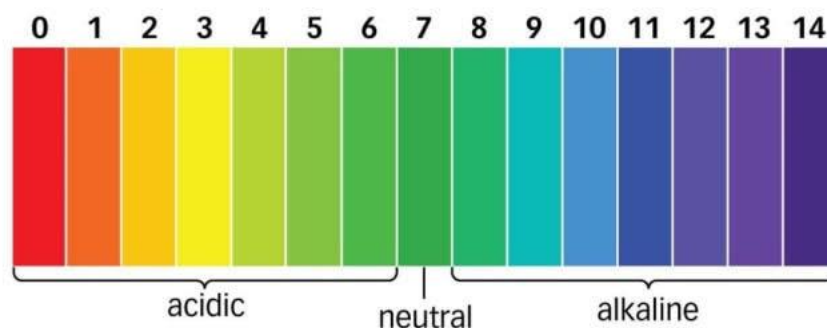
The PH Scale

Figure 5-11

Some very special dyes show color changes when placed in contact with basic, acidic or neutral substances. These dyes are varied and the litmus paper we talked about earlier is just one of them. Litmus papers are a treated dye obtained from lichens which is soluble in water. The color change is based on the concentration of ions in any given solution. Red litmus papers turn blue on exposure to alkaline or basic substances while blue litmus papers turn red when placed in contact with acidic substances. Neutral litmus papers could be either blue or red on account of how basic or acidic something is.

The depth of the color shows the extent of the acidity or alkalinity of something. As seen above in the image, it is a scale. A value of 1 shows that the substance is strongly acidic with a deeply red color to indicate that. Neutral substances are green and alkaline substances go from blue to deeper shades of purple. This variation is the PH scale.

"The PH scale is a graduated measure of how acidic or alkaline a substance is."

Litmus paper is just one indicator of this scale. Other indicators used are phenolphthalein, bromothymol blue and methyl orange. You would use some of these in laboratory work.

Neutralization

Here at last. We needed to understand acids, bases and PH to explain neutralization reactions. Now you know the properties of acids and bases and it was all nice knowing them but in neutralization reactions all those properties in a sense, become destroyed. When acids and alkali react, they form substances that differ greatly from them and their combining qualities. They form salt and water.
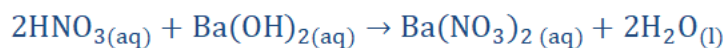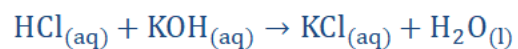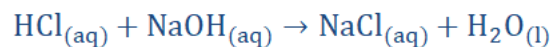
$$Acid + Base \rightarrow Salt + Water$$
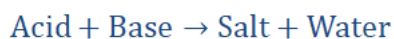
How they differ you ask? In order to answer that we'll have to note the properties of salts and so understand what they are.

Salts are formed when acids and bases react. They are usually powdered in form. They are of two types; **acid salts** and **basic salts**. Acid salts are salts that produce acidic solutions, while basic salts on dissolution in water produce hydroxide ions and hence basic or alkali solutions. You may be wondering where our common everyday table salt fits in all this. Table salt is NaCl and is a **neutral salt**. These salts are neither acidic nor basic and thank God for that because if NaCl were either of those we would suffer from mostly tasteless food.

Salts have many colours, from transparent (as in sodium chloride) to violet (as in potassium permanganate). They also come in a variety of tastes from salty (sodium chloride; and funny how the 'salt' is 'salty') to bitter (magnesium sulfate) and even sweet (lead diacetate). It may be tempting to think lead diacetate candy is a good idea but that sweetness may be the last thing you ever taste; so no. Other salts can be savory or umami. They show odor variety as well as varying solubility.

The point made here is that salts have a plethora of variations that differ from the properties shown by their parent acids and bases. The following are examples of neutralization reactions.

$$HCl_{(aq)} + NaOH_{(aq)} \rightarrow NaCl_{(aq)} + H_2O_{(l)}$$

$$HCl_{(aq)} + KOH_{(aq)} \rightarrow KCl_{(aq)} + H_2O_{(l)}$$

$$2HNO_{3(aq)} + Ba(OH)_{2(aq)} \rightarrow Ba(NO_3)_{2\ (aq)} + 2H_2O_{(l)}$$

An everyday example of a neutralization reaction is when you take antacid tablets or solutions when suffering from stomach acidity. The antacid solution is alkaline as you can probably notice on account of it being quite slimy. When you take it, it neutralizes the acid in your stomach and returns the PH of your stomach to a neutral state. So thank neutralization when you feel better after taking a spoon of Gestid next time.

We've been talking so long that you **definitely** need a drink. I may also need one of those antacids. Why not take a while off to rest? When you're back we would be trying to understand exactly how and why any of these reactions happen; we would be discussing chemical kinetics.

Chemical Kinetics

We have already defined chemical kinetics as the study of the rates of reactions. In kinetics we attempt to know how fast or slow reactions go and the underlying reasons for those rates. We have also defined a reaction rate as the time taken for a reaction to reach completion. For instance;

$$2HNO_{3(aq)} + Ca_{(s)} \rightarrow Ca(NO_3)_2 + H_{2(g)}$$
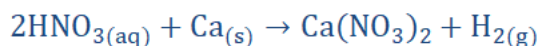
The rate of this reaction can be obtained by noting how fast the Ca is used up by the acid, and how fast the products are formed. So reaction rate can be observed by noticing **how the masses of reactants decrease** or are used up and products are formed.

Another way to note the rate of a reaction is to **measure the changes in concentration** of the participating entities as the reaction proceeds. In the example above, we can measure the decrease of concentration of the reactants and subsequent increase in product concentration.

Sometimes the volumes of reactants alter on account of a reaction taking place. When we measure **volume changes** of reactants in the formation of products, we can measure rates of reactions.

In precipitation reactions we could measure how fast or slow a reaction is by measuring **how much precipitate** is formed at the end of the reaction.

Some reactions rates can be measured when the reactants change color as the products are formed. The speed at which **the color changes** occur correlates to how fast the reaction is going.

When the **PH of a reaction changes**, measuring the rate of that change could show if the reaction is fast or slow.

The collision theory

I am not the biggest fan of Mixed Martial Arts (MMA) but anytime I happen to watch a fight I stay at the edge of my seat because the matches are just so thrilling. Here I find men and women throw punches and kicks at each other but remain standing, ready to punch and kick again until one of them takes a bad enough hit and reacts to it by falling.

Figure 5-12 MMA fighters…make me feel the need to work out more

What happens in these fights is somewhat analogous to what happens when reactant particles give rise to products. The particles of the reactants constantly collide with each other however just like not all hits in a fight can cause a knock out, not all collisions between reactant particles lead to products. Those that do lead to the formation of products are termed **effective collisions.** Effective collisions are not as many as non-effective ones. The non-effective collisions simply result in the rebounding of the particles the same way a ball bounces off a wall. Imagine if every hit given and received by MMA fighters were effective enough to cause knockouts. I don't think the fights would be nearly as interesting. But what happens when the reacting particles collide? The thing is that the particles on collision break their existing bonds so new bonds can be formed. A visual aid may be more effective in explaining this.
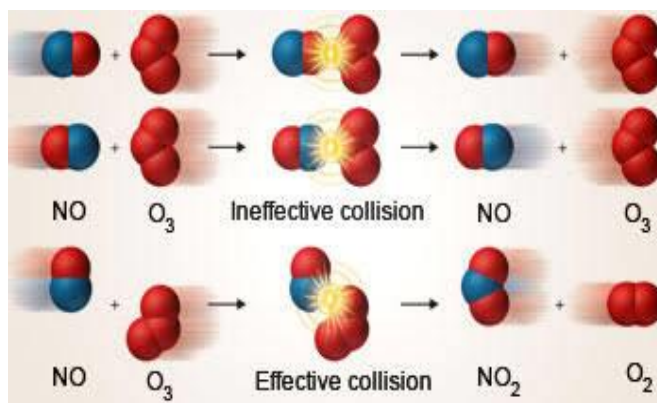

Figure 5-13 Illustrating effective collisions

As you can see from the image the ineffective collisions do not result in product formation but the particles reacting simply bounce off each other. Effective

collisions result in bonds breaking and new bonds being formed thereby forming products.

This is all nice and dandy but there's a catch. Before reactant particles can break bonds, they must have sufficient energy to do so. This energy that they are required to have to initiate bond breaking is called the **activation energy.** Imagine if one of the MMA fighters mentioned above had indulged in eating unhealthy and watching TV frequently prior to the match. She would never have had enough energy to knock out her opponent who may have been working out a lot during that time. So in the same way reactant particles must possess enough energy to break bonds and form products. If the reactant particles have energies lower than the activation energy, the reaction would not occur but if their energies exceed the activation energy, it would.

The lowering of this activation energy is what makes catalysts so good at speeding up the rates of reactions. When added, a catalyst lowers the activation energy, making it easier for reactant particles to form products and hence do it much faster. Negative catalysts do just the opposite by raising the activation energy instead.

Practical ways to make reactant particles exceed this energy barrier may be to heat up the reacting system or introduce an electric current.

Factors that influence reaction rates

Some factors can affect how fast or slow a reaction may be. So far we have seen some of these factors. We have seen catalysts, have considered particle collision rates and have noted the energy the reactant particles must possess to induce a reaction. But apart from these there are many other factors that could affect the rate of a reaction. These are listed below.

1) Concentration of reactants: Concentration of a substance is defined as how much of the substance (amount of a substance) is available in a given volume of solution. It is also known as the molarity of a substance and is measured in molsdm^{-3}.

$$\text{Molar concentration} = \frac{\text{Number of moles of solute}}{\text{Volume of solution}}$$

When there is a high concentration of reactants present in a solution, chances are that the frequency of collisions would be correspondingly high

meaning that effective collisions would also increase. This of course means that more of the products would be formed. The reverse of this (low reactant concentrations) would mean that less amount of product formation would occur.

2) State of reactants/surface area of reactant particles: Remember when we spoke of solid state synthesis? We mentioned that the only way to have the solids react well was to grind them into powdered form so as to increase the area of contact between them. So increasing how much area of the reactant particles are in contact with each other would ensure that greater collisions take place. Imagine having to cause a reaction between substances of different states; maybe a liquid and a solid. If you do not grind the solid to increase its surface area and just dump it in there, chances are you would get very little reactant collisions because not much surface area is there to ease the reaction process.

3) **Nature of reactants:** Some solvents react much more easily with solutes or other substances than some others. This has nothing to do with the mechanism of reaction itself, but has much more to do with the inherent properties of the solvent. A piece of Na may not react when dropped in kerosene or some other inert liquid, but on slight contact with water we get an explosive reaction (check the first image of this chapter to see this). This does not only apply to solvents. When the same piece of Na is placed in N_2 gas it seldom reacts. It reacts with hydrogen however, forming sodium hydride (NaH). A recent study has even shown that sodium reacts with the inert gas He, though this only occurs under very special conditions where He gas is placed under a high enough pressure. So we see that the nature of the reactants affects the reaction rate.

4) **Temperature:** If you raise the temperature of a reaction system, you increase the energy acquired by the reacting particles. As we have already learnt before now, when these particles acquire this energy they move about much more frequently and with much speed colliding with one another. This therefore means that the chances of obtaining effective collisions rise and so the reaction rate proceeds much faster. Below is a graph showing the relationship between the temperature (in K) and rate of a reaction to prove this.
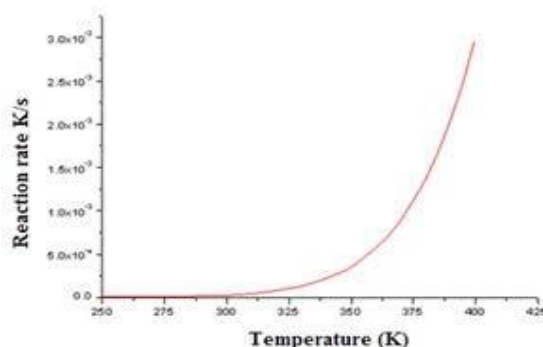
Figure 5-14 Graph of Temperature against Reaction rate

5) Catalyst effect: Catalysts can speed the rate of a reaction by lowering the activation energy of the reaction system allowing the reactant particles overcome the energy barrier. In order to slow down the rate of a reaction they do this by increasing the activation energy, making it difficult for the reactant particles to get pass this energy barrier. One amusing way to picture the effects of catalyst is to imagine playing basketball with a small child. You know that asking the child to score some baskets is virtually impossible, so in order to ensure that the game is over quickly you lower the hoop every time he tries to shoot because you know that if left to him, you may never leave that place. You play the part of a positive catalyst, the hoop is the activation energy, the child is the reactant particle and making the basket is the reaction. Let's say Anno is now playing basketball with the same child. Being such a kind young man, whenever it is time for the child to score he raises the hoop even higher. He's a negative catalyst and not even the child's tears could affect him.

And there we have it. Now you know the factors that affect the rates of chemical reactions. Let's move on to answering some questions and see how much you've really learnt.

SUMMARY

- Chemical kinetics is a branch of chemistry that deals with the study of the rates of chemical reactions.
- A combination (or synthesis) reaction is a reaction that occurs when two or more reactants come together to form a product. The general form of a combination reaction is A + B → AB.
- A decomposition reaction involves the breakdown of a compound into two or more simpler forms. The general form of a decomposition reaction is AB →A+B.
- The three types of decomposition reactions are thermal decomposition, electrolytic decomposition and photolytic decomposition reactions.
- A catalytic reaction is one that involves the use of catalysts to aid in the formation of products.
- Catalysts are substances that alter the rates of chemical reactions but are themselves chemically and quantitatively unchanged when the reactions conclude.
- Catalysis is divided into homogenous and heterogeneous catalysis.
- Catalysts can be organic or inorganic catalysts. Inorganic catalysts are largely positive or negative.
- Thermal dissociation reaction is a reaction that involves the splitting of a compound or more complex entity into its simpler compositions.
- Thermal dissociation reactions are mostly reversible, thermal decomposition reactions are mostly irreversible and largely naturally occurring.
- Reversible reactions are reactions that can proceed in both directions.
- A displacement reaction is one in which one or more atoms of an element displace another/others in a compound.
- There are two types of displacement reactions: single (substitution) and double (metathesis) displacement reactions.
- Any reaction that involves the evolution of heat and typically involves burning in oxygen is a combustion reaction.
- A precipitation reaction is defined as one that involves the reaction between two soluble reactants in an aqueous solution to form products; one of which is insoluble.
- Precipitation reactions can be single or double displacement reactions.

- Solid state reactions are reactions between solid substances to form products.

- Reduction and oxidation reactions are to halves of a single process.

- A redox reaction involves the transfer of electrons between reacting species, oxidation is the loss of electrons while reduction is the gain of electrons.

- The oxidation state of an element shows the number of electrons of an atom of the element that is involved in bond formation with the atom of another element.

- An acid is any substance that increases the hydronium (or oxonium) ion (H_3O^+) concentration in solution.

- There are Arrhenius, Bronsted-Lowry and Lewis acids depending on definition.

- Acids may be divided into strong acids and weak acids.

- Acids have a number of characteristics. They can also be classified as organic and inorganic acids.

- A base is a substance that increases the hydroxide ion (OH^-) concentration in water.

- There are Arrhenius, Bronsted-Lowry and Lewis bases depending on definition.

- Bases may be divided into strong bases, weak bases, super bases and solid bases.

- Bases have a number of characteristics. A soluble base is known as an alkali.

- The basicity of an acid shows how many replaceable hydrogen ions there are in one molecule of the acid.

- The PH scale is a graduated measure of how acidic or alkaline a substance is.

- Neutralization reactions are of the form; $Acid + Base \rightarrow Salt + Water$

- Chemistry can be found in all things; including MMA fights.

- The collision theory describes the underlying processes that occur in chemical reactions.

- Factors that affect the rate of chemical reactions are Reactant concentration, state of reactants/surface area, nature of reactants, temperature and catalyst effects.

MNEMONICS

There is so much to remember here. Think up awesome, easy to remember mnemonics as usual. Make it personal if you like. I'll try to suggest some.

- The types of chemical reactions:

N   S   P   C   D   R   R   T   C   D   C

N – Neutralization reaction

S- Solid-State synthesis

P- Precipitation reaction

C – Combustion reaction

D- Displacement reaction

R-Redox reaction

R-Reversible reaction

T-Thermal dissociation reaction

C-Catalytic reaction

D-Decomposition reaction

C-Combination reaction

What have you come up with? I love animals so naturally I thought of 'No Sane People Can Drive Red Rabbits To Catch Dancing Cats'. Don't think about it too much. I don't even think sane people should catch random dancing cats let alone drive red rabbits. Just enjoy how insane it is as that aids memory and then recall the mnemonic during exams or whenever you need it.

- Factors that influence reaction rates:

N   S   C   T   C

N – Nature of reactants

S- State of reactants/surface area

C- Concentration of reactants

T – Temperature

C- Catalyst effect

I thought of 'No Students Care To Combust'; As it should be. The last thing we want is having combusting students and that's why you have such strict supervision in the laboratory because as you may have learnt by now, with chemistry almost anything is possible. Don't forget to make this personal if you must so you can remember better.

REVISION QUESTIONS

1. Define chemical kinetics.
2. List and explain eleven types of chemical reactions.
3. Explain the collision theory
4. What are the factors that affect the rates of chemical reactions?
5. A substance X reacts to form 25g of oxygen gas at a pressure of 40 atm at standard temperature.
   a) Calculate the volume of the O_2 produced.
   b) What is the molarity of O_2?
6. Determine the oxidation states of the following;
   a) S in H_2SO_4
   b) P in NaH_2PO_4
   c) Na in Na_2O_2
   d) Fe in $FeCl_2$(oxidation state for Cl in the compound is -1).
   e) Sb in Sb_4O_6

CHAPTER 6: MORE ON REACTIONS

Energy Changes

(a) Thermal energy
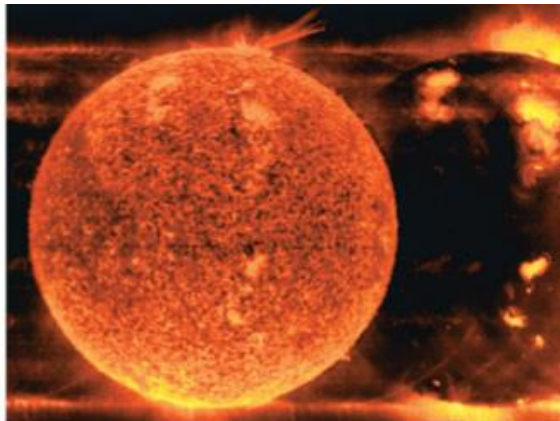
(b) Radiant energy

(c) Electrical energy

(d) Nuclear energy

(e) Chemical energy

Energy is known simply as the capacity to do work. This means that whatever contains energy can expend it in some way to achieve an aim. In chemical reactions there is usually a difference in energy between reactants and products. When we talk about energy in chemistry we usually try to understand the energy interactions between reactants and products. All matter contains energy. When you eat food you obtain energy from the food and become able to carry out your activities. I can only type this long because I ate a hearty dinner. You can only sit so long for classes because you consume egusi soup, yams, pasta, rice or whatever it is that you eat that is of course edible. Your generators work because they use up the energy stored in the form of

petrol. Cars also run because they have fuel- which is energy-stored in them. Energy is all around us and as we have always done with things that are all around us we put on our deerstalker hats and become academic Sherlocks to deduce their underlying chemistry.

Chemical thermodynamics

Chemical thermodynamics is a field of chemistry that deals with the study of how energy changes impact chemical reactions. It can also be defined as the study of the interactions between heat and work in a chemical system. There are **three fundamental laws of chemical thermodynamics** that guide these energy interactions in chemistry.

The first law of thermodynamics

This is also known as the law of conservation of energy and states that **energy can only change from one form to another but can never be created or destroyed**. This law therefore implies that the total energy in the universe is constant. A good way to visualize this law is to picture a relay race. Imagine that the different runners on the field are the different energy forms and that the baton is the energy. In a standard relay race as one runner reaches the next he or she passes on the baton. Only a single baton is required in the duration of time for the race and no new batons are added or removed until the race is concluded. The law of conservation of energy is somewhat similar. Energy changes form just as in the case of the runners but it's the same amount of energy as in the baton in that regulated and closed environment; that environment can be taken to be the track.

The law can be represented quantitatively in the following way;

$$E_U = E_S + E_{Su}$$

E_U is the energy of the universe, E_S is the energy of a specific system and E_{Su} is the energy outside that system; all the other energy in the universe. So we see that the total energy in the universe can be taken to be the energy of whatever system is under consideration in addition to the energy surrounding that system, outside it.

We said that the energy in the universe is constant. This implies;

$$0 = E_S + E_{Su}$$
$$E_S = -E_{Su}$$

This last equation shows that whatever we do to the energy system affects the energy of its surroundings. If we subtract from the energy of a system we add to the total energy in the surroundings and vice versa. It is an important concept and a succinct representation of the first law of thermodynamics. But what kind of energy are we talking about? There are many *forms* of energy in the universe, but when we boil them all down we realize that there are only three main *types* of energy. We know these types of energy as **kinetic**, **potential** and **internal energy**.

Kinetic energy is defined as energy due to motion. In order to make a football move on the field, footballers kick the ball. They apply a force to the ball and so are said to do *work* on it. This work is then gained in the form of energy by the ball. The faster the ball moves, the greater the energy. There would be more kinetic energy gained by a football kicked by Ronaldo than one kicked by me on account of the fact that Ronaldo would as a result of practice place sufficient force on the ball, hence more work would be done on it and consequently more kinetic energy obtained.

Potential energy on the other hand is defined as the energy due to the position of a body relative to others. It can also be defined as energy at rest. Relative to a person on the ground, a person standing on the balcony of a tall building has greater potential energy. This is because the person above has a greater capacity to do work on the occasion that he falls; but we hope he won't.

Atoms and molecules possess potential and kinetic energies. We have thoroughly explored how molecules possess and utilize kinetic energy. Now however our main concern is the third type of energy as it concerns chemical reactions the most.

Internal energy (U)

This energy type concerns the positions of elementary entities as well as their interactions. These interactions take the form of translations, vibrations and rotations. Translational motion of micro particles involve a change in the object's position; as in moving from one point in space to another. Vibrations are more repetitive motions of particles and rotations are akin to circular movement around a point. These motions in addition to potential energies make up the internal energy of a micro particle system.

Unlike measuring the kinetic and potential energies of macro bodies, directly measuring energy at an atomic level falls on the scale of difficult to impossible. On account of this, chemists measure estimates of this energy by measuring internal energy changes that occur in the system instead. The change in internal energy can then be obtained by applying the formula;

$$\Delta U = q + w$$

Where ΔU = Change in internal energy

q = Heat transferred to or from the system

w = Work done to or by the system

In the event that heat is lost from a system into the surroundings, q is accompanied by a '-' sign to show this. When a system gains heat from the surroundings it is denoted +q.

In the same way if work is done by the system on the surroundings, w becomes –w. In the reverse of the situation; when the surroundings do work on a system it becomes +w.

The unit of energy is the joule.

Enthalpy

For a system existing at some given pressure and volume, the enthalpy of that system is defined as the sum of its internal energy and the product of its pressure and volume. Enthalpy therefore comprises the entire heat content of a system. It shows how much heat is either absorbed by a system or released into its surroundings. It is usually shown as a change in enthalpy to account for changes in energy between one state and another, such as between reactants and products.

$$\Delta H = \Delta U + \Delta PV$$

Where ΔH = Change in enthalpy

ΔU = Change in internal energy

ΔPV = Change in the product of pressure and volume

In systems of constant pressure, the formula changes to give;

$$\Delta H = \Delta U + P\Delta V$$

Since the pressure is constant;

$$\Delta H = \Delta U + 0$$
$$\Delta H = \Delta U$$

Recall that;

$$\Delta U = q + w$$

With constant temperature and pressure no work is done to or by the system and so w become 0 hence;

$$\Delta U = q$$
$$\Delta H = q$$

At constant temperature and pressure, the enthalpy of a system is therefore equal to the heat absorbed by or given off by the system. This shows that at constant pressure in the event a system gives of heat to the surroundings and hence has a negative value, the enthalpy of that system would also be negative. When the system absorbs heat and has a positive value as a result, the enthalpy assumes a positive value as well. For a chemical reaction the enthalpy content can be obtained by subtracting the enthalpy of the reactants from the enthalpy of the products.

$$\Delta H = H_{products} - H_{reactants}$$

Standard Enthalpy

In order to allow for more accurate measurements, scientists set up a standard that is used in energy calculations and experiments regarding chemical reactions.

"The standard enthalpy of a reaction is defined as the enthalpy change that occurs when molar amounts of substances undergo chemical reactions under standard conditions."

It is denoted by $\Delta H^{\ominus}$.

The standard conditions mentioned here mean that the temperature is at 298 k (25°C), the pressure is 100 kPa (another unit for pressure) and the substances involved have concentrations of 1 mol dm^{-3}. Standard enthalpy changes vary depending on the type of reaction considered. They are standard enthalpies of formation, combustion, solution and neutralization.
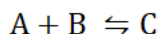
Standard enthalpy change of formation($\Delta H_f^{\ominus}$)

The standard enthalpy of formation of a substance is defined as the enthalpy change that occurs when a mole of the compound is formed from its elements under standard conditions.

To understand this, let's consider the reaction below.

$$C_{(g)} + O_{2(g)} \rightarrow CO_{2(g)} \quad \Delta H_f^{\ominus} = -393.5 \text{ KJ/mol}$$
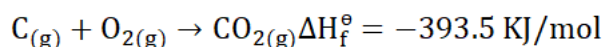
This shows that heat is lost in the formation of the product and that the standard heat of formation of CO_2 is -393.5 KJ/mol. In order to know how to solve for the heat of formation we would need to know the standard enthalpies for the product and reactants. For;

$$A + B \rightleftharpoons C$$

$$\Delta H_f^{\ominus} = \Delta H_f^{\ominus}[C] - (\Delta H_f^{\ominus}[A] + \Delta H_f^{\ominus}[B])$$

In order to easily arrive at the standard enthalpies we would have to apply a special formula which we would discuss shortly.

Standard enthalpy change of combustion($\Delta H_c^{\ominus}$)

It is no surprise that combustion concerns the release of relatively large amounts of energy in the form of heat.

The standard enthalpy change of combustion is therefore defined as the enthalpy change that occurs when one mole of a substance burns completely in an oxidant (usually oxygen) under standard conditions.

Just as we saw in the standard heat of formation, the standard heat of combustion is dependent on the same standard conditions of temperature, pressure and molarity.

Standard enthalpy change of solution($\Delta H_s^{\ominus}$)

Lattice energy is known as the energy required by the molecules of solvents to break up bonds of ionic solutes so as to allow dissolution. *Hydration energy* is the energy then required to hydrate the split up ions. These two process allow for the release or absorbtion of heat by the solution.

The standard enthalpy change of solution is the enthalpy change that occurs when one mole of a substance dissolves completely in a solvent to form a solution under standard conditions.

Standard enthalpy change of neutralization($\Delta H_n^{\ominus}$)

Heat changes in neutralization reactions usually involve the release of energy as acids and bases combine to form salt and water.

The standard enthalpy of neutralization of a reaction is defined as the enthalpy change that occurs when when one mole of H^+ from an acid react with one mole of OH^- from an alkali to form a mole of H_2O under standard conditions.

Exothermic and endothermic reactions
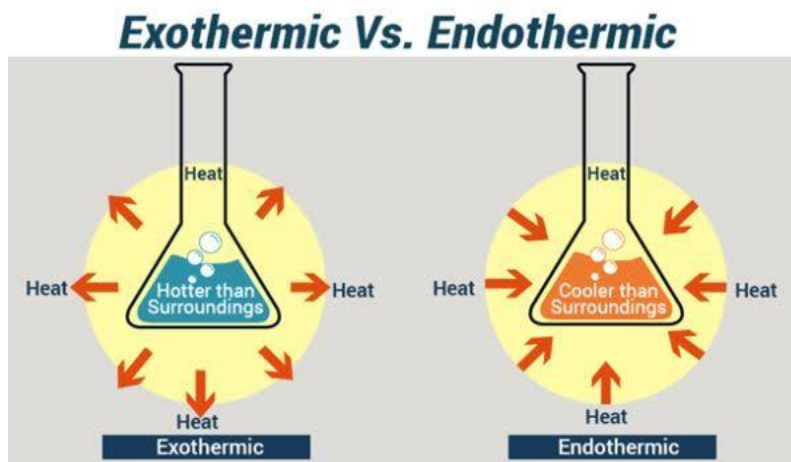
Chemical reactions involve the evolution or absorption of heat. In many cases both heat removal and gain could occur for a single reaction. However there is always a net process that favors one of the processes more. When a reaction involves the release of heat energy to the surroundings it is termed an **exothermic reaction.** When it largely involves absorbing heat from the surroundings it is an **endothermic reaction**. The reaction vessel of an exothermic reaction is hotter than its immediate surroundings, while the reaction vessel of an endothermic reaction is colder than its immediate surroundings.

"An exothermic reaction is one that involves the release of heat from a reaction system into the surroundings."

"An endothermic reaction or process involves the gaining of heat from the surroundings to a reaction system."
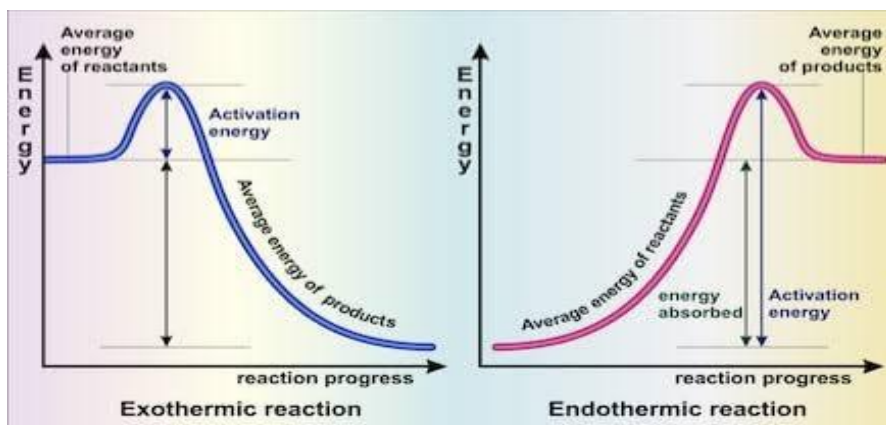
Figure 6-2 Energy level diagrams of exothermic and endothermic reactions.

We know from the collision theory that effective collisions between reactant particles give rise to products. We also know that the particles must overcome an energy barrier and possess the activation energy needed to form products. In an **energy level diagram**, this activation energy is shown to be the difference between the energy of the reactants and the energy of the products. For an exothermic reaction the energy of the reactants exceeds the energy of the products. The reaction therefore demands less energy input but releases excess energy in the form of heat into the surroundings. It also explains why ΔH is negative when applied to the equation;

$$\Delta H = H_{products} - H_{reactants}$$

For an endothermic reaction, the energy of the products surpasses that of the reactants. More energy is required from the surroundings to exceed the energy barrier and arrive at the activation energy so that products can be formed. This energy is usually in the form of heat. ΔH is positive in endothermic reactions for the same reason it is negative in exothermic reactions and so we can tell whether a reaction is exothermic or endothermic by noting what sign accompanies the ΔHᵉ. For instance;

$$2Na_{(s)} + 2H_2O_{(l)} \rightarrow 2NaOH_{(g)} + H_{2(g)} \Delta H_f^{\ominus} = -362.52 \text{ KJ/mol}$$
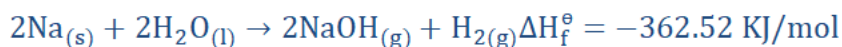
This reaction is exothermic as we can see the negative sign of $\Delta H_f^{\ominus}$ showing that heat has been evolved. A large amount too! This makes sense when we consider the vigorous nature of the reaction between sodium and water.

$$CO_{2(g)} + H_{2(g)} \rightarrow CO_{(g)} + H_2O_{(l)} \quad \Delta H_f^\ominus = +42 \text{ kJ/mol}$$

In the equation above we note a positive $\Delta H_f^\ominus$ and so we can tell that the reaction is endothermic.

Reactions and Bond energies

We've been talking about the structures atoms form for quite some time. When atoms of elements come together they form such wonderful compounds but how do they hold together? Imagine a bowl of popcorn. You are watching your favorite episode of BBC Sherlock or Africa Magic's The Johnsons when your imaginative mind wonders what honey and popcorn would taste like. You decide to do just that but after a while you find out that the individual popcorn pieces stick together. The honey acts as some kind of 'glue' holding the popcorn together. It would never have been possible for the popcorn to stick together without this makeshift 'glue'.

We can compare that to bonds and bond energy. Bonds must exist between atoms to hold them together. These bonds require energy to keep them so as well as energy to break them apart. The energy required by compounds to hold atoms of their elements together or break them apart is termed **bond energy.**

"Bond energy is defined as the energy required for the breaking or forming of atomic bonds."

When the bond existing between atoms is strong, greater energy would be required to break them apart. They are therefore said to have high bond energies. On the other hand, when the bond existing between them is weak, less energy would be needed to split them and so they possess low bond energy. A H-H (hydrogen to hydrogen) bond for instance has an average bond energy of 432 kJ mol^{-1} as opposed to an I-Br (Iodine to bromine) bond of only 175 kJ mol^{-1}. Also, a C≡N (carbon to nitrogen triple bond) has average

bond energy of 891 kJ mol^{-1} while a C≡N (carbon to nitrogen double bond) has bond energy of 615 kJ mol^{-1}.

Two other concepts accompany bond energy and these are **bond order** and **bond length.**

Bond order shows the number of pairs of electrons that engage in bond formation between two atoms. For C-C for instance, we know that two pairs of electrons-one donated by each atom-is involved in bond formation between them (remember that a 'dash' is equivalent to an electron pair). The bond order is therefore 1. In a doubly bonded carbon to carbon pair of atoms (C=C) we see that we now have four pairs of electrons; hence two bonds. The bond order here becomes 2. What would the bond order be for a triple bond? How about no bonds at all? I'll wait.

 The general formula for finding bond order is;

$$\text{Bond order} = \frac{\text{N0 of electrons in antibonding} - \text{N0 of electrons in bonding}}{2}$$

The *antibonding* electrons consist of those electrons that are not involved in bond formation, while the *bonding* electrons are those that are.

Bond length exists in inverse proportion to bond order. This means that when bond order is increased, bond length falls and vice versa. When the number of bonding electrons between atoms is increased, there is a greater pull or force of attraction between them and consequently the length of the bond between them shortens or reduces. It is measured in **picometers.** The greater the number of picometers between atoms, the lower the bond order. Single bonds therefore have greater bond lengths than triple bonds and triple bonds have greater bond order than single bonds.

Hess law of heat summation and the Born-Haber cycle

Remember when I promised to show you a relatively easy way to calculate enthalpy without having to memorize the enthalpies of all substances? Well this is what I was referring to. We would be applying the Born-Haber cycle and Hess law of heat summation to achieve this. The Born-Haber cycle was put forward by two scientists; Max Born and Fritz Haber. Another scientist named Kasimir Fajans had independently formulated it and so I find the

concept to be more accurately identified as the Born-Haber-Fajans cycle. That's really long so maybe we'll stick with Born-Haber.

Hess law explains that the total enthalpy change of a reaction is actually the sum of the enthalpy changes of individual processes involved in the reaction. The Born-Haber cycle is an aspect of Hess law that specifically concerns ionic substances. The cycle attempts to explain why ionic solids are so stable and why these solids despite similar structures differ greatly from each other in terms of physical characteristics. It has been shown that enthalpy is not enough to account for these. In order to do so the concept of**lattice energy**was introduced. We had spoken of lattice energy earlier when we defined the standard enthalpy change of formation. It turns out that lattice energy is the reason for the stability of ionic solids as well as explains why their physical characteristics such as solubility differ so much.

Lattice energy can be defined in two ways. It can be defined as *the energy required by an ionic substance to split it apart into simpler gaseous constituents.* Since it requires the addition of energy here this process is endothermic. It is also defined as *the loss of energy usually in the form of heat when an ionic substance is formed by simpler gaseous constituents.* As you can probably tell this process is exothermic.

In order to truly understand the Born-Haber cycle we have to examine five enthalpies that accompany most chemical reactions. These are very, very briefly explored below. They would be explained more thoroughly later.

Ionization energy: This is the amount of energy needed to remove an electron from a neutral atom. It is denoted by ΔH_{IE}.

Dissociation energy: This is the energy needed to break a substance apart into its constituents. It is denoted by ΔH_{dis}.

Electron affinity: This is the amount of energy needed to remove an electron from a neutral atom. It is denoted by ΔH_{EA}.

Sublimation energy: This is the amount of energy needed by a substance to change its state from solid to gaseous without passing the liquid state. It is denoted by ΔH_{sub}.

Internal energy: Do we need to explain this one? Yes? Alright. This is the energy possessed by a body due to the heat associated with it and the work

done on it or by it. It is denoted by U. When ionic solids are concerned the internal energy becomes equal to the latent energy.

In order to analyze the Born-Haber cycle of a reaction we add up these energies and find out the total enthalpy change. As an example, if we need to find out the total enthalpy change for the formation of a substance the equation for the Born-Haber cycle would be taken as;

$$\Delta H_f^\ominus = \Delta H_{IE} + \Delta H_{dis} + \Delta H_{EA} + \Delta H_{sub} + U$$

This is also:

$$\Delta H_f^\ominus - (\Delta H_{IE} + \Delta H_{dis} + \Delta H_{EA} + \Delta H_{sub} + U) = 0$$

Let's try to apply the cycle to an actual problem so we don't seem like we're speaking some cryptic language. Let's apply this to the formation of table salt; NaCl.

The formation of NaCl is divided into a number of stages. The enthalpies of these stages can be measured but as we stated earlier the lattice energy cannot. The $\Delta H_f^\ominus$ for Nacl for instance can be experimentally derived and is gotten as -411 kJ mol^{-1}.

The first stage of the formation of NaCl is sublimation, where the solid Na **sublimes** into atomic gaseous, simpler form. The process here is endothermic since heat is required to achieve this.

When this is concluded, each neutral atom then releases the single valence electron on its valence shell. In doing so, they release energy which we know as **ionization energy**.

Dissociation then occurs as molecular chlorine (Cl_2) splits into single atoms. The process is endothermic as energy is absorbed to achieve this.

Remember the electrons given away by the individual Na atoms? The Cl atoms accept the electrons. Energy in the same magnitude as the **electron affinity** is evolved by this exothermic process.

Finally, the two gasses composed of individual ions combine to form their solid offspring; the NaCl molecules. Energy is being released which we know as **lattice energy**.

Did you count the number of processes involved here? Who would have thought that the single reaction had so many levels to it?
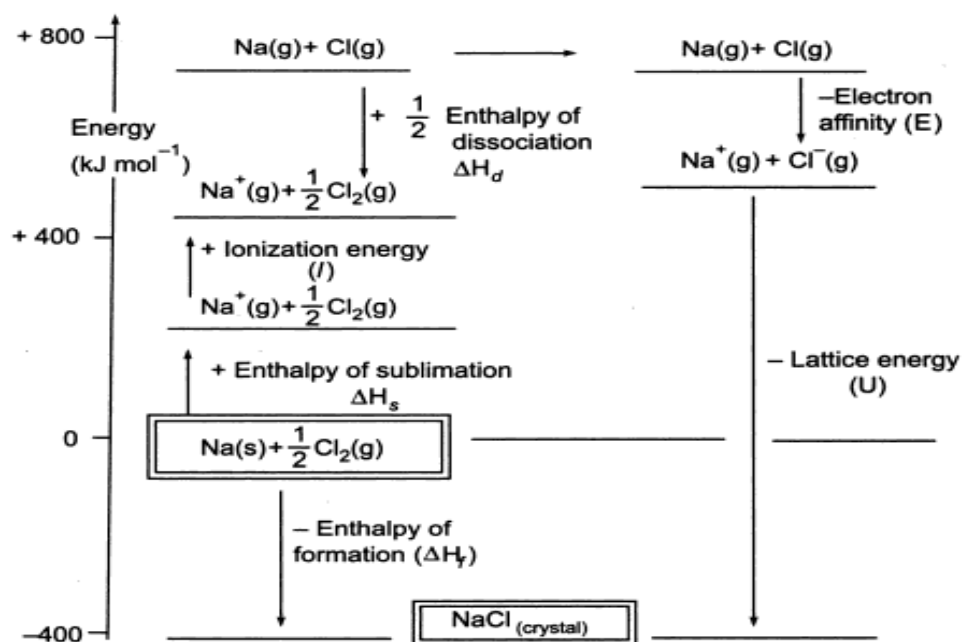
Figure 6-3 Born-Haber cycle for the formation of NaCl.

The above is the Born-Haber cycle for the process we have explained above. Now we would apply the associated formula to find the lattice energy for the reaction.

Experimentally the following enthalpies for the formation of NaCl have been derived;

$$\Delta H_f^{\ominus} = -411 \text{ kJ mol}^{-1}$$

$$\Delta H_{sub} = +107 \text{ kJ mol}^{-1}$$

$$\Delta H_{IE} = +502 \text{ kJ mol}^{-1}$$

$$\Delta H_{dis} = +121 \text{ kJ mol}^{-1}$$

$$\Delta H_{EA} = -355 \text{ kJ mol}^{-1}$$

$$U = ?$$

Inputting these into the equation;

$$\Delta H_f^{\ominus} = \Delta H_{IE} + \Delta H_{dis} + \Delta H_{EA} + \Delta H_{sub} + U$$

$$U = \Delta H_f^{\ominus} - (\Delta H_{IE} + \Delta H_{dis} + \Delta H_{EA} + \Delta H_{sub})$$

$$U = -411 - (502 + 121 - 355 + 107)$$

$$U = -411 - (502 + 121 - 355 + 107)$$

$$U = -411 - (375)$$

$$U = -411 - 375$$

$$U = -786 \text{ kJ mol}^{-1}$$

And now we see that the lattice energy of the formation of NaCl is -786 kJ mol⁻¹. Isn't it just wonderful how we can determine this without leaving our desks? You can thank Germain Hess, Max Born, Fritz Haber and Kasimir Fajans for that.

Entropy (ΔS)

Figure 6-4

I was never a destructive kid but this was certainly one of my more interesting topics. I just felt that I didn't have to think too hard to get it. It just made sense. Order might be harder to spot but disorder? Well that's everywhere and in more ways than one too. The idea of entropy, put quite simply concerns how disordered a system is.

"Entropy is a thermodynamic property that describes the degree of disorder of a system."

Entropy simply tells you how spread out elementary particles are; how inconsistent their arrangement is meaning the extent to which they deviate from consistency. It is denoted by S. When considering initial and final states we use ΔS instead so as to show that the entropy of the system has changed. From this definition, can you tell what has the highest entropy between a solid, liquid and gas? I'll wait.

If you truly thought about that you'd realize that substances in the gaseous state tend to have greater 'randomness' or 'disorder' than substances that are liquids or solids. It is therefore no surprise when we learn that entropy is dependent on temperature; meaning that the greater the temperature of a

system the greater the disorder and vice versa. At a constant temperature entropy is related to enthalpy in the following way:

$$\Delta S = \frac{\Delta H}{T}$$

Gibbs free energy (ΔG)

Josiah Willard Gibbs in 1873 published papers that showed that the direction of a chemical reaction could be predicted. By utilizing his new found study scientists could tell if a reaction was spontaneous or non-spontaneous. Spontaneous reactions do not require added energy to proceed while non-spontaneous reactions needed external energy pumped into them in order for them to take place. Gibbs' equation combined enthalpy and entropy into a single equation and he identified this direction of a reaction or its capacity to do work as *available energy*. But today we know it as *free energy.*

"The free energy of a chemical reaction is defined as a measure of its available energy to do work."

Free energy is quantitatively equivalent to the subtraction between the enthalpy of a system and the product of its entropy and temperature. It is usually presented as a change in free energy (ΔG) under standard conditions (at constant temperature and pressure).

$$\Delta G = \Delta H - T\Delta S$$

Figure 6-5 Time moves in one direction

Have you ever wanted to travel in time? Maybe back to when you were little or perhaps to right some wrongs or steal Einstein's work and come back to the present so you can claim it instead! Maybe you should not attempt the last one but for the first two I imagine you may not mind that if it was a pleasant time for you. In that case allow me to tell you that you just can and it's fairly easy; so easy that I can say it in just six words- break the second law of thermodynamics.

"The second law of thermodynamics states that for an isolated system, the entropy is always increasing and so never decreases."

What does time have to do with entropy? I'll show you. In nature there is always an increase in disorder. This fact can only be negated if systems are in a state of continuous reversibility; meaning that every occurrence would be reversed. This is however not how the universe works. Most natural occurrences are irreversible. This is because systems in the universe are attempting to achieve thermodynamic stability. The second law is the reason why each time you clean up your room it gets messy again. No matter how neat you are and what systems you put in place, it does. I may not have been the tidiest child but I was sensibly tidy and yet once upon a time I was convinced there was a monster under my bed who took some sick pleasure in messing up my room. Another instance can be found in ice blocks. Why do they always melt when left on their own but never freeze up even more? Why does heat flow from a hotter body to a colder one and not the other way

around? The second law tells us that disorder is always increasing. It is a one way street and there are no U-turns. As the universe is a sort of isolated system, time is no exception to this rule. It is subject to ever increasing entropy and so proceeds in only one way. The next time you watch the movie 'Back to the Future' for the hundredth time and wonder why we can't travel back in time, blame the second law of thermodynamics. It can be expressed as;

$$\Delta S_{universe} = \Delta S_{surroundings} + \Delta S_{system}$$

Now we know what this law is, how does it apply to chemical reactions? The second law can be restated as;

"For an isolated spontaneous system, the entropy is always increasing."

We had mentioned spontaneity before now when we spoke of free energy. The second law can be described in terms of free energy, entropy and enthalpy as we would soon see.

$$\Delta S_{universe} = \Delta S_{surroundings} + \Delta S_{system}$$

$$\Delta S_{surroundings} = -\frac{\Delta H}{T}$$

Substitute into the equation;

$$\Delta S_{universe} = -\frac{\Delta H}{T} + \Delta S_{system}$$

Multiply both sides of the equation by T;

$$T\Delta S_{universe} = (T) - \frac{\Delta H}{T} + T\Delta S_{system}$$

$$T\Delta S_{universe} = -\Delta H + T\Delta S_{system}$$

$$-T\Delta S_{universe} = \Delta H - T\Delta S_{system}$$

-TΔS is the free energy ΔG that we discussed earlier. We can therefore see how the second thermodynamic law relates to the free energy of a system.

$$\Delta G = \Delta H - T\Delta S$$

The third law of thermodynamics

The third law is concerned with *absolute zero.* You may recall that we have mentioned absolute zero a few times; for instance when we spoke of the Bose-Einstein condensate. It is the lowest possible temperature that can be reached by a body. Below this temperature motion ceases. This law asserts that as temperature approaches the absolute zero which is equivalent to 0 K, entropy tends to a constant value hence motion ceases since entropy becomes 0. In some academic circles it is known as **Nernst's law** since it was stated by the chemist Walther Nernst between the years of 1906 to 1912.

The laws of thermodynamics appear to me to be a perfect story of thermodynamics. We begin with a fundamental universal principle that the energy of the universe is constant and cannot be altered since it is to the best of our knowledge a closed system. We then proceed to learning that this same universe will always have a continuous increase in disorder and finally we learn that in approaching absolute zero, the entropy would become constant and motion will cease. We see the beginning, growth and death of nature in just a few pages.

The last paragraph was just to prove that chemists can be poetic too. It's that time again for some well deserved rest. When you return, it'll be the usual.

SUMMARY

- Energy is the capacity to do work.
- There are three types of energy: potential, kinetic and internal energy.
- Potential energy is energy due to position, kinetic energy is energy due to motion and internal energy is energy due to the positions and interactions of elementary entities.
- Chemical thermodynamics is a field of chemistry that deals with the study of how energy changes impact chemical reactions. There are three laws of chemical thermodynamics.
- The first law of chemical thermodynamics states that energy can neither be created nor destroyed.
- The enthalpy of that system is defined as the sum of its internal energy and the product of its pressure and volume.
- The standard enthalpy of a reaction is defined as the enthalpy change that occurs when molar amounts of substances undergo chemical reactions under standard conditions. It is denoted by $\Delta H^{\ominus}$.
- There are standard enthalpies of formation, solution, neutralization and combustion.
- An exothermic reaction is one that involves the release of heat from a reaction system into the surroundings while an endothermic reaction or process involves the gaining of heat from the surroundings to a reaction system."
- Bond energy is defined as the energy required for the breaking or forming of atomic bonds.
- Bond order shows the number of pairs of electrons that engage in bond formation between two atoms.
- Bond length exists in inverse proportion to bond order. This means that when bond order is increased, bond length falls and vice versa.
- Hess law explains that the total enthalpy change of a reaction is actually the sum of the enthalpy changes of individual processes involved in the reaction.
- The Born-Haber cycle is an aspect of Hess law that specifically concerns ionic substances.
- Lattice energy can be defined as the energy required by an ionic substance to split it apart into simpler gaseous constituents. It can also be defined as the loss

of energy usually in the form of heat when an ionic substance is formed by simpler gaseous constituents.

- Ionization energy is the amount of energy needed to remove an electron from a neutral atom. It is denoted by ΔH_{IE}.
- Dissociation energy is the energy needed to break a substance apart into its constituents. It is denoted by ΔH_{dis}.
- Electron affinity is the amount of energy needed to remove an electron from a neutral atom. It is denoted by ΔH_{EA}.
- Sublimation energy is the amount of energy needed by a substance to change its state from solid to gaseous without passing the liquid state. It is denoted by ΔH_{sub}.
- Entropy is a thermodynamic property that describes the degree of disorder of a system.
- The free energy of a chemical reaction is defined as a measure of its available energy to do work.
- The second law of thermodynamics states that for an isolated system, the entropy is always increasing and so never decreases.
- The third law of thermodynamics states that as temperature approaches the absolute zero which is equivalent to 0 K, entropy tends to a constant value hence motion ceases since entropy becomes 0.

MNEMONICS

Did you find anything that made you feel the need for a mnemonic today?

- The standard enthalpies:

<div align="center">

S   C   N   F

</div>

S– Solution; as in "Standard enthalpy of **solution.**"

C- Combustion; as in "Standard enthalpy of **combustion.**"

N- Neutralization; as in "Standard enthalpy of **neutralization.**"

F – Formation; as in "Standard enthalpy of **formation.**"

'Sandwiches Can Now Fly.' No comments.

REVISION QUESTIONS

1. What is Chemical Thermodynamics?
2. List and state the three fundamental laws of chemical thermodynamics.
3. What is energy?
4. List and define the three types of energy.
5. Define the following:
   a) Enthalpy
   b) Standard enthalpy
   c) Standard enthalpy of formation
   d) Standard enthalpy of neutralization
   e) Standard enthalpy of solution
   f) Standard enthalpy of combustion
   g) Bond energy
   h) Bond order
   i) Lattice energy
   j) Bond length
   k) Ionization energy
   l) Dissociation energy
   m) Sublimation energy
   n) Electron affinity
   o) Entropy
   p) Free energy
6. Differentiate between exothermic and endothermic reactions.
7. State Hess' law.
8. Explain with the aid of a diagram the Born-Haber cycle.
9. Why is it nearly impossible to move backwards in time?

CHAPTER 7: EQUILIBRUM

If we were to summarize the aim of all that exists based on what we've learnt so far, we would roughly do so in only a word-balance. Balance seems to be nature's theme. Everything that occurs, every reaction, the very elementary particles themselves seek some sort of stability. Even in a philosophical sense the essence of life lies in achieving balance. But we are scientists so let's stick to science. Even when systems seem to be in chaos it is all on account of attempts to attain stability. It almost seems paradoxical but we have seen from the second thermodynamic law that this is so.

In chemical reactions the story is no different. The utility we obtain from products appears to be just a by-product of the real reason for the reaction. That reason is balance or more appropriately called **chemical equilibrium**.

"Chemical equilibrium in a reversible reaction occurs when reactant and product concentrations do not alter with time, and the rate of the forward reaction is equal to the rate of the backward reaction."

Equilibrium is of two major types. These are static equilibrium and dynamic equilibrium. Two other types of equilibrium are homogenous and heterogeneous equilibrium; dependent on the phases of the reacting substances and their products. When the reactants and products are in the same phase the equilibrium is homogenous while in different phases it is heterogeneous. Our main focus here however is on static and dynamic equilibrium. In static equilibrium stationary balance is attained. Both sides of the system are balanced and remain so. An example of this sort of equilibrium can be found in a see-saw. If two children of roughly the same weight sit at equal distance from each other on a see-saw they can be said to attain static or stationary equilibrium. In the second type of equilibrium however, the entities of the system are in constant motion. Consider two men juggling for instance. As they juggle, each man throws a number of bottles to the other man and the other man does the same. When the number of bottles passed on to each other reaches a constant value, each man receives and passes

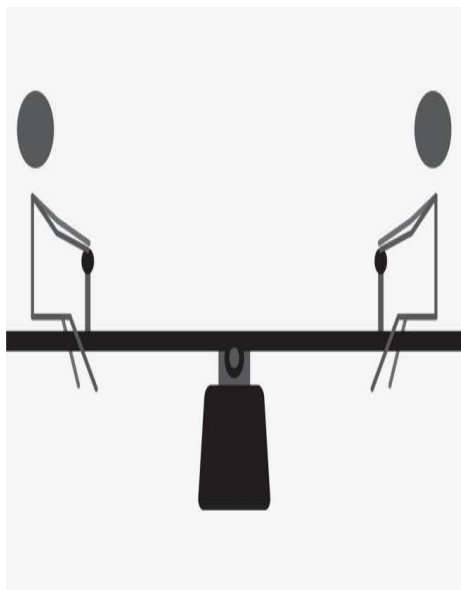bottles at the same rate. In this situation a dynamic equilibrium can be said to be attained.

Figure 7-1 (a & b) A balanced see-saw and passing in bottle juggling illustrate the two types of equilibrium.

Chemical reactions exhibit dynamic equilibrium. They can also only occur in closed systems. This is because as reactants combine to form products, the products form the reactants as well. If you are keen am certain you recognized this to be a *reversible reaction.*A closed system is one that is unaffected by external forces or changes. In reactions the closed system is usually in the form of a sealed vessel where nothing can get out and nothing can get in. In that case when reactants form products, the products recombine to form the reactants. This process continues until the rate at which the reactants combine to form the products becomes equal to the rate at which the products recombine to form the reactants. When this point is reached we can say that the reaction has reached a dynamic equilibrium. For instance let us consider the following reaction;

$$NO_{2(g)} + CO_{(g)} \rightleftharpoons NO_{(g)} + CO_{2(g)}$$
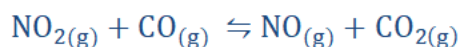
The *forward reaction* consists of the reaction between the reactants while the *backward reaction* concerns the combination of the products to reform the reactants. If this reaction occurs in a closed system equilibrium would be attained. However when it is conducted in an open system such as when the lid of the vessel is removed, the reaction takes place in only one direction as the CO_2 and NO being gasses would escape into the atmosphere and so would not be able to recombine to form CO and

NO_2. For this reason having the reaction take place in a closed system is crucial which in the case of this example is a tube. At the beginning, we find that the reddish-brown NO_2 and CO react to form the products NO and CO_2 which are both colorless gases. With some time however we begin to notice that the CO_2 and NO recombine to form the reactants because the reddish-brown color of NO_2 returns to the tube. When the concentrations of reactants and products become equal we can then say that it is in dynamic equilibrium.

Equilibrium Constant (K) and the law of mass action

We would not be good chemists if we did not find a way to quantitatively measure the equilibrium that accompanies chemical reactions. This measure is known as the equilibrium constant and is denoted by K. In order to do this we would have to star in 'the law of mass action' featuring Guldberg and Waage.

I could not help myself because the names *Gulberg* and *Waage* in association with the terms *law of mass action* just simply sounded like a blockbuster movie. Let me rephrase that a bit.

The law of mass action was explored by two scientists; Cato M. Gulberg and Peter Waage between the years of 1864 and 1879. Their aim was to understand the behaviors exhibited by substances and solutions in dynamic equilibrium. They came to the conclusion that concentration was a highly dependent factor on how equilibrium was arrived at by solutions. This concentration is what they had termed 'mass action'.

"The law of mass action states that under conditions of constant temperature, the rate of a reaction is dependent on the active masses (concentration) of the reactants."

For a reaction;

$$jA + uB \rightleftharpoons mC + pD$$
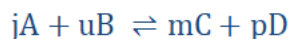
A and **B** are the concentrations of reactants A and B respectively while **C** and **D** are the concentrations of the corresponding products. **j**, **u**, **m** and **p** are amounts in moles. The forward reaction has a rate of r_1 while the backward reaction has a rate of r_2.
Based on the law of mass action; for the forward reaction;

$$r_1 \propto [A]^j . [B]^u$$

$$r_1 = k_1 . [A]^j . [B]^u$$

The same applies for the backward reaction;

$$r_2 \propto [C]^m . [D]^p$$

$$r_2 = k_2 . [C]^m . [D]^p$$

K is known as the *velocity constant*. It describes the relative speed of particle collision for each half of the reaction i.e. for the forward and backward reactions independently. In dynamic equilibrium, the rate of the forward reaction becomes equal to the rate of the backward reaction.

$$r_1 = r_2$$

$$k_1 . [A]^j . [B]^u = k_2 . [C]^m . [D]^p$$

$$\frac{k_1}{k_2} = . \frac{[C]^m . [D]^p}{[A]^j . [B]^u} = K$$

This final K is the equilibrium constant of the entire reaction at a particular temperature since the constant alters with a change in temperature. It helps to show the relationship between reactants and products in a state of equilibrium.

Le Chatelier's principle

I have a cousin who as a kid was obsessed with having things his way. Indeed as children we all were intransigent about how we wanted things but he took it to a whole new level. If you placed an object in a different location from where he put it he had the habit of throwing tantrums and just returning it back there. You can imagine how Christmas dinners were with him.

Just like my cousin, chemical reactions can be terribly 'stubborn' but we can't blame them for being so. Imagine if someone asked you to stand under the mid day sun but you knew that you would be better under a shade. I am quite sure you'll pick the shade over the scorching sun any day. Chemical reactions do something similar. Whenever a reaction approaches or is at equilibrium and we change any of its conditions, it changes so as to cancel the effect of that change and assume a state of equilibrium. This is the idea behind the principle that was put forth by Henry Louis Le Chatelier in 1884.

"Le Chatelier's principle states that for a system in equilibrium, whenever any of its conditions are altered its equilibrium shifts so as to annul the effect of that change."

We would now examine how the different possible alterations such as changes in temperature, concentration, pressure and catalyst affect the equilibrium of a system and in so doing we would note how Le Chatelier's principle may be applied.

Effect of change in temperature on equilibrium constant

When a chemical system attains equilibrium and the temperature of the system is increased, its response to that change depends on what sort of reaction it is,i.e. whether it is an exothermic or endothermic reaction.

For an exothermic reaction;

$$A + B \rightleftharpoons C + D; \quad \Delta H = -ve$$

When the heat of the system is increased, the system accommodates this change by releasing the excess heat into the surroundings. On doing so it favors the backward reaction meaning it favors the formation of the reactants. By favoring the backward reaction the equilibrium position shifts to the left and the equilibrium constant K decreases.

In the event that the temperature of the system is lowered, the equilibrium position shifts to the right and the forward reaction is favored. This means that product formation is favored and the equilibrium constant K increases.

As for an endothermic reaction;

$$J + U \rightleftharpoons M + P; \quad \Delta H = +ve$$

On increasing the heat of the system the equilibrium position shifts to the right, favoring product formation, hence the forward reaction. This also means that K increases. When the temperature falls, the equilibrium position shifts to the left, the backward reaction is favored meaning that reactant formation is favored and K decreases.

Let's put this in a table so as to clear away any residual confusion.

Temperature of system	Endothermic reaction	Exothermic reaction

1. **Increase in temperature**	• Equilibrium position shifts to the right. • Favors the forward reaction, i.e. product formation. • Equilibrium constant (K) increases.	• Equilibrium position shifts to the left. • Favors the backward reaction, i.e. reactant formation. • Equilibrium constant (K) decreases.
2. **Decrease in temperature**	• Equilibrium position shifts to the left. • Favors the backward reaction, i.e. reactant formation. • Equilibrium constant (K) decreases.	• Equilibrium position shifts to the right. • Favors the forward reaction, i.e. product formation. • Equilibrium constant (K) increases.

Effect of change in pressure on equilibrium constant

When dealing with pressure we consider gaseous systems. When gaseous reactants react to form products equilibrium is attained when the number of moles of reactants and the number of moles of products are equal. A change in pressure implies that this balance of moles is tampered with and so there becomes an uneven distribution in the number of moles of each side. This means that the number of moles on one side exceeds the other. There is therefore uneven pressure. The system tries to fix this in accordance with Le Chatelier's principle by favoring the opposite of what external constraint has been applied. For instance if one were to increase the pressure of a system in equilibrium, the system would fix this by favoring the reaction with a reduction in pressure. The adverse response would be gotten when one tries to reduce the pressure of the system. Have a look at the equation below.

$$N_2O_{4(g)} \leftrightharpoons 2NO_{2(g)}$$
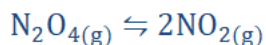
Looking at the forward reaction we observe that there is an increase in the number of moles as reactants convert to products since 1 mole of N_2O_4 gives 2 moles of NO_2. The number of moles is proportional to the pressure, so that a higher mole number indicates

a higher pressure. What this implies is that a reduction in pressure favors the forward reaction while a corresponding increase in pressure favors the backward reaction.

**Effect of change in concentration on equilibrium constant**

We know that equilibrium is attained when the concentrations of reactants and products are equal. In situations where the concentration of the reactants increase, the system corrects this imbalance by favoring the forward reaction, allowing greater product formation so that equilibrium can be attained.

Effect of catalysts on equilibrium

Catalysts have no effect on the equilibrium of a reaction. This is because they only work by lowering the activation energy of the reaction. They however indirectly affect the attainment of equilibrium by speeding up the reaction and in so doing allow for equilibrium to be arrived at much faster. In the absence of a catalyst, equilibrium would still be attained but at a much slower rate.

Examples of equilibrium in chemical reactions

1) **The Haber-Bosch process**: This is an industrial process used in the manufacture of ammonia for large scale purposes. It was discovered by our friend Fritz Haber (remember him?) and Carl Bosch when they had found a more man-made method of nitrogen fixation by converting atmospheric nitrogen into ammonia due to its reaction with hydrogen. This reaction is an exothermic one and in a closed system under the right conditions, it has been noted that the ammonia formed reverts to the substances from which it was made.

$$N_{2(g)} + 3H_{2(g)} \leftrightharpoons 2NH_{3(g)} \quad -91.8\,\text{kJ}\,\text{mol}^{-1}$$
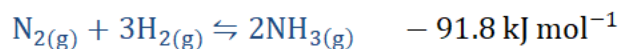
If we increase the temperature of the reaction, being an exothermic one it would adjust to annul that change by favoring the backward reaction (hence favoring the formation of N_2 and H_2) thereby shifting the equilibrium position to the left and decreasing the equilibrium constant. However if we lower the temperature more NH_3 would be formed (favoring the forward reaction), the equilibrium position would shift to the right and the equilibrium constant would increase.

What would happen if we increase the pressure? We can see that on the reactant side we have a total of 4 moles of the reactants while on the product side there are 2 moles of the product. Increasing the pressure would therefore mean that the forward reaction would be favored leading to greater product formation. Decreasing the pressure would do the opposite of that, favoring the backward reaction and increasing the amount of reactants formed.

As for concentration, an increase in the amount of reactants would always favor the forward reaction leading to the production of more NH_3.

Finally, catalysts such as iron (Fe) are used to speed up the reaction, and hence make the reaction arrive at equilibrium much faster.

2) **Acid-Base equilibrium**:

Acids appear to only exhibit acidic properties when they are dissolved in water. This is because on dissolution the hydrogen ions dissociate and the acidic substance then exhibits those characteristics known to be displayed by acids. On dissolution, the hydrogen ions become oxonium or hydronium ions (H_3O^+) which we have already explored.

$$HA_{(aq)} + H_2O_{(l)} \leftrightharpoons H_3O^+_{(aq)} + A^-_{(aq)}$$
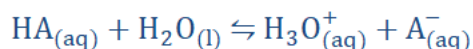
In most equations however the H^+ notation is preferred to allow for ease in analysis and for convenience.

$$HA_{(aq)} + H_2O_{(l)} \leftrightharpoons H^+_{(aq)} + A^-_{(aq)}$$
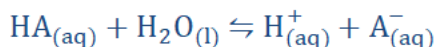
Where A = Acid

Several other substances that are non acidic on contact with water do not display acidic properties but those that are acidic do such as HCl and nitrate. The funny thing is that when these substances are not dissolved in water they have none of those unique acidic characters. They do not turn blue litmus red or produce hydrogen when they react with metals. Imagine how you act in different situations. When you are in the presence of certain people such as your perhaps; strict parents (if they are) you may not be as ecstatic as when you are in the presence of your peers. Acidic substances in the same way react differently. Their acidic properties only show when they dissolve in water.

As a side note, I feel it a duty to warn that you should never on any condition pour water into acid, but pour the acid into the water instead. This is because the reaction between acids and water is very exothermic and very dangerous as it

could splash and give you a new face that won't be as pretty as your present face. Do not even attempt the acid and water mix unless you are instructed to do so and under supervision.

In an acid-base reaction, a solution of water and hydronium is known as an acid-base conjugate pair. This conjugate pair is responsible for the formation of weak acids and bases in solution. Usually in acid-base equilibrium;

$$\text{Strong acid} + \text{Strong base} \rightleftharpoons \text{Weak acid} + \text{Weak base}$$
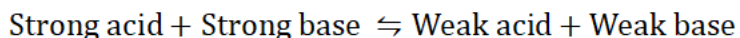
The side of the equation with the weaker acid and base is normally favored, hence favoring the backward reaction, leading to the formation of more reactants. The equilibrium constants for acid-base reactions can be given by the equations:

$$K_a = \frac{[H_3O^+][A^-]}{[HA]}$$

For an acid and;

$$K_b = \frac{[OH^-][BH^+]}{[B]}$$

For a base.

SUMMARY

- Chemical equilibrium in a reversible reaction occurs when reactant and product concentrations do not alter with time, and the rate of the forward reaction is equal to the rate of the backward reaction.

- The law of mass action states that under conditions of constant temperature, the rate of a reaction is dependent on the active masses (concentration) of the reactants.

- Le Chatelier's principle states that for a system in equilibrium, whenever any of its conditions are altered its equilibrium shifts so as to annul the effect of that change.

- The equilibrium constant K can be affected by the effect of changes in temperature, pressure, concentration and the effect of a catalyst.

- The Haber-Bosch and acid-base reactions are two instances of equilibrium in chemical reactions.

MNEMONICS

Did you find anything that made you feel the need for a mnemonic today?

- The factors that affect the equilibrium constant in chemical reactions:

<div align="center">

P   C   C   T

</div>

P– Pressure; as in "Change in **pressure.**"

C- Concentration; as in "Change in **concentration.**"

C- Catalyst; as in"Effect of **catalysts.**"

T – Temperature; as in "Change in **temperature.**"

 'People Crave Cutting Tires.' Or 'People Cut Cakes Together.' (Some people…)

REVISION QUESTIONS

1. Differentiate between reversible and irreversible reactions.
2. State the law of mass action
3. State Le Chatelier's Principle.
4. State and explain the factors that affect the equilibrium constant K of a recation.
5. When can one say the equilibrium of a reaction has been reached?
6. State and explain two instances of equilibrium in chemical reactions.
7. Differentiate between reaction types that absorb more energy from the environment and those that lose more energy to the environment in terms of **increase in temperature** and **decrease in temperature** with regards to equilibrium constants.

CHAPTER 8: ELECTROLYSIS

If you wanted to astound me as a kid by showing me a magic trick all you had to do was tell me that you could produce electricity from water. I mean, I would not have believed you but you would certainly have blown my ten year old mind to bits with that claim. As I got older I was more and more convinced that it was all hogwash; at least until I began learning about it. You couldn't just do it. Water and electricity could never mix…or could they?

That's what we would be attempting to learn in this chapter. We would like to know how such 'magic' can come to be. However there is no magic here. We have already seen that the atom is way stranger than we expected and on that account weird things are possible. Don't you just love chemistry?

Figure 8-1 Michael Faraday conducting an electrolytic reaction in the lab.

One of the finest minds that ever existed had its home in the skull of Michael Faraday, a scientist who made incredible advancements in the fields of electromagnetism and electrochemistry. It is true that the concept of electrolysis had been known and preceded his discourse on it but he had given an exhaustive description of the phenomenon. He also coined the very term *electrolysis* which we now use as we please and as suggested by Rev. William Whewell, another impressive scientific mind and polymath. Other great figures like Anthony Carlisle, William Nicholson, Alessandro

Volta, Humphry Davy, Luigi Galvani and a host of others contributed to the colorful history of the phenomenon known as electrolysis; which we can unfortunately not examine here. However indulge in reading that history when you can. As your 'invisible' guide I assure you it is worth the effort.

So what is electrolysis all about?

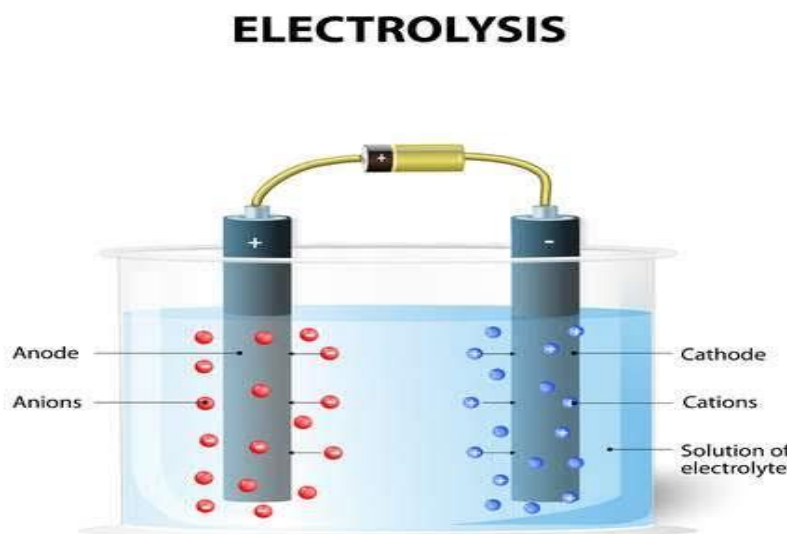There are three important proponents to an electrolytic system. These are the **electrolyte**, **the direct current and external circuit** and the **electrode**.

ELECTROLYSIS

Figure 8-2 Electrolytic cell

The **electrolyte** is the substance that on dissolution produces free ions. As you know ions are charged atoms, and so they possess charges. They also carry electric currents.

"An electrolyte is a substance that produces free ions on dissolution in water."

Electrolytes when in solid form do not conduct electricity and so are not suitable for use as electrolytes since the ions are 'locked' and are not free to move about in order to conduct electricity. **Direct current** is passed into the solution of the electrolyte and as it does it breaks down the compound (electrolyte) into simpler substances. When this happens the ions are passed across an **external circuit** which consists of a battery and some wires. They do not just leap into the wires however but pass through conductors known as **electrodes. There** are two types of electrodes known as the **anode** and the **cathode** (if it sounds a lot like anions and cations; it's supposed to. You'll soon get to know why).These electrodes allow the ions pass and then get deposited as the products of the reaction. The entire circuit is known as an **electrolytic cell** or **circuit.**

Now let's put this all together and see if we can paint a vivid picture of electrolysis and reach a good definition. In electrolysis, an electric current is passed through an external circuit into a solution of an electrolyte. The electrolyte breaks down and forms free ions. These ions pass through the appropriate electrodes through the external circuit and are deposited as the products of the electrolytic decomposition reaction (hope you remember this).

"Electrolysis is defined as the process by which an electrolyte undergoes decomposition when an electric current is passed through it."

I think that's about right.

I am quite sure your curious mind is not satisfied with this. You want to know what's going on at an atomic level. In that case, you are truly becoming a full blown chemist. Walk with me.
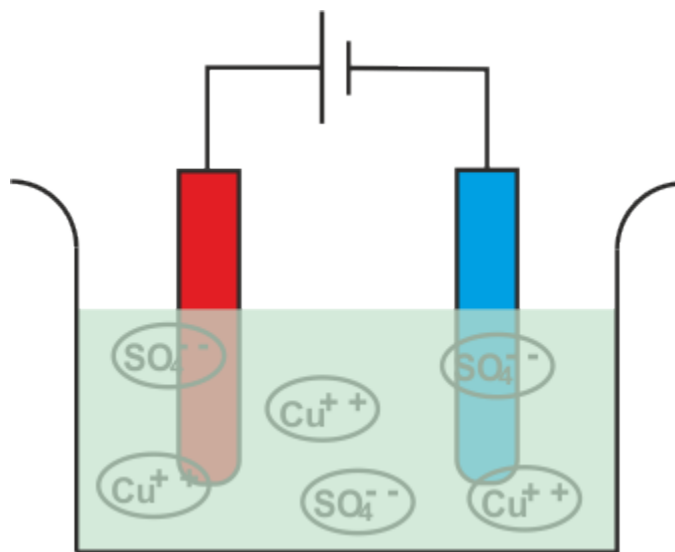
Figure 8-3 Electrolysis of $CuSO_4$

We already know that there are three parts to this process: the electrolyte, the electrodes and the direct current. We know their definitions and have a general idea of what they do for the process to come to be.

More specifically however, if we could just magnify the process by a large amount we would find that $CuSO_4$ being an electrovalent compound consists of a large number of ions, some positive and others negative. The positive ions (atoms having more protons than electrons) are called cations while the negative ions (other atoms that have more

electrons than protons instead) are anions. In the absence of an electric current to break down the electrolyte however, neutral atoms tend to move about in the solution. But in the event that the electrolyte breaks down we find these ions swimming aimlessly about in solution absorbed by something – the electrodes.

There are two kinds of electrodes in an electrochemical cell, just like there are two kinds of ions. There are electrodes that have an affinity (tend to attract) positive ions. Because the ions they attract are positive, it is easy to infer that these electrodes must be negative. Since they attract **cat-**ions they are known as **cat-**hodes.

On account of their similar names this singular fact confused me a lot in secondary school. I had thought that cations being positive, meant that cathodes were also positive and vice versa, but that isn't true. Cations are positive, cathodes are negatively charged. In a similar way, **an-**odes attract **an-**ions and since anions are negatively charged, anodes are positively charged electrodes.

Sometimes a single electrode is introduced into a solution of its salt and electrode potential is set up between the solution and the electrode as in the image above (**fig.3**). As seen, neutral atoms on the electrode (Copper plate in this case) lose electrons and fall into the solution as positively charged ions (cations). As more and more of them do this the electrode becomes negatively charged and the solution positively charged. As you may already know, when this happens, a *potential difference* is set up between them. This potential difference is what we have already referred to as the **electrode potential.**

Half-cell reactions: Two electrodes

It is important that you realize especially at the level you are that all you learn is not just for the purpose of passing exams or bragging about how much you know, but for the noble aim of helping to solve some problems faced by the world today using what you have acquired. Don't be alarmed, I would only remind you of this fact throughout our discourse just so that in knowing, you will assist when and how you may now or in the not so distant future.

I have to admit though that the previous paragraph only came about because of what we would be discussing which is; **electrochemical cells.** The world is facing an energy crisis today. It is up to us chemists to find new ways or refine old ones so that we have sufficient energy that pose less harm to the environment. As you know energy can be transformed from one form to another. A popular energy transformation is the chemical to electrical energy conversion. The device that makes this possible is known as an

electrochemical cell. In electrolysis we could also achieve electrical energy from chemical energy. An example of such a cell is shown below.
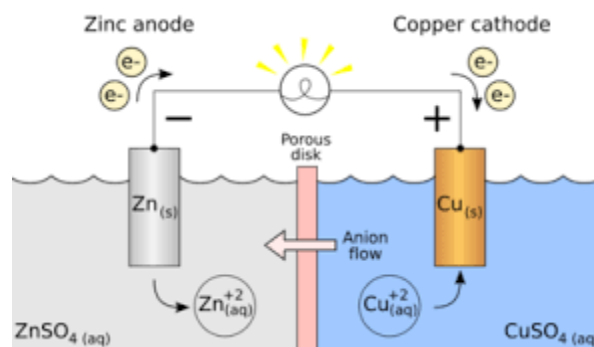

Figure 8-4 Electricity from a Zn-Cu electrochemical cell

Redox (recall reduction and oxidation reactions) take place in electrolysis because atoms either give up electrons or gain electrons to form ions in the process. In the reaction illustrated above, Zn atoms on the Zn electrode being electronegative lose two electrons each with ease and in so doing acquire a net positive charge (form cations). These cations then go into the solution and so the solution ($ZNSO_4$) becomes positively charged. The excess electrons however remain on the Zn electrode, making the electrode negatively charged. From this Zn *halfcell* (half of the electrochemical circuit) the excess electrons on the electrode then flow along the wire to meet the Cu electrode on the other side (the second halfcell). The ions on the Cu electrode then take up the deposited electrons and become neutral atoms. Since the electrode is therefore not negatively charged, it then functions as the cathode of the reaction. We then see that the Zn electrode which is in this case the anode, becomes depleted and the cathode 'grows' in size for as long as the reaction occurs. Since electrons were taken up by the Zn electrode and then given away to the Cu electrode, it is safe to say that the process of oxidation (electron loss) occurs at the anode (Zn electrode) while reduction (electron gain) occurs at the cathode (Cu electrode). The complete reaction is:

$$Zn_{(s)} + Cu^{2+}_{(aq)} \rightarrow Zn^{2+}_{(aq)} + Cu_{(s)}$$
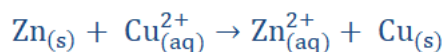
The half-cell reactions are shown below. Oxidation occurs at the anode:

$$Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$$
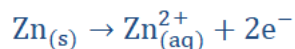
Reduction occurs at the cathode:

$$Cu^{2+}_{(aq)} + 2e^+ \rightarrow Cu_{(s)}$$

The Ionic theory

The behavior of electrolytes is a very interesting thing to consider when dealing with electrolysis. Why they dissociate, the form in which they conduct electricity and other factors are things we would closely look at here. So walk with me.


Figure 8-5 Svante Arrhenius

It is the year 1887 and we find the pensive Arrhenius with an experimental set up before him. He barely notices our presence. I take an interest in his set up while you read through his notes. You see that he is working on a theory, attempting to explain how electrolysis occurs by showing that the electrolyte somehow dissociates into ions when met with a direct current or melted in solution. Let's take a look at this.

You already know that electrolysis occurs due to the passage of ions. But why is this so? Why can't neutral atoms do this as well? Arrhenius explained this by stating that neutral atoms could not conduct electricity. The electrolyte must be dissociated into ions and a direct current must be introduced so as to align these ions, meaning that the positive ions would then be attracted to the negative electrode and likewise the negative ions would cling to the positive electrode. The dissociation that occurs in electrolytes is known as **ionization** which I am certain you recall.

The Arrhenius theory for a long time painted a convenient picture of electrolysis. However it was discovered that even in solid form, strong alkalis and salts still contained oppositely charged ions, hence they did not require dissolution to be formed. It was then observed, that the freeing of the ions in solution was what was required for electrolysis

as the ions must exist in the structure even before dissolution could occur. This means that even without dissolution occurring there can exist ions.

$$NaCl_{(s)} \rightarrow Na^+_{(aq)} + Cl^-_{(aq)} \ldots (1)$$

$$Na^+Cl^-_{(s)} \rightarrow Na^+_{(aq)} + Cl^-_{(aq)} \ldots (2)$$
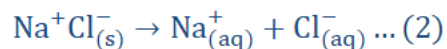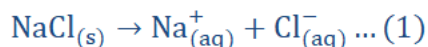
Of the two equations listed above, which do you consider to be a more accurate depiction of the dissolution of NaCl? I'll wait.

"Arrhernius' ionic theory states that when an electrolyte is dissolved or melted in water, its molecules dissociate into ions that move freely in solution."

Ions and preferential discharge

No matter how much we would like it to be so for simplicity's sake, ions are not discharged all *willy nilly* at the electrodes to form neutral atoms. Some ions are favorites and are hence preferred during ion discharge and this is due to a number of reasons which we would discuss shortly. Remember that a number of ions are usually involved in the electrolytic process as the electrolyte may contain more than one ion as in our NaCl example above where Na^+ and Cl^- ions are involved.

$$Na^+Cl^-_{(s)} \rightarrow Na^+_{(aq)} + Cl^-_{(aq)}$$

The above equation however is not complete. When expanded…

$$Na^+Cl^-_{(s)} + H_2O_{(l)} \rightarrow Na^+_{(aq)} + H^+_{(aq)} + Cl^-_{(aq)} + OH^-_{(aq)}$$

We can see from the above that there are two anions (negative ions) and two cations (positive ions) so which would be preferably discharged at each electrode? (The anode and the cathode). We need to know which ions would be the 'chosen ones' and why. Below are the reasons.

Reasons for Preferential Discharge of Ions

The Electrochemical Series

K$^+$	F$^-$
Na$^+$	SO$_4{}^{2-}$
Ca^{2+}	NO$_3{}^-$
Mg^{2+}	Cl$^-$
Al^{3+}	Br$^-$
Zn^{2+}	I$^-$
Fe^{2+}	OH$^-$
Sn^{2+}	
Pb^{2+}	
H$^+$	Ease of discharge
Cu^{2+}	increases
Ag$^+$	

Figure 8-6 The Electrochemical Series

1. **Position on the Electrochemical Series:** The electrochemical series is a series that shows the arrangement of elements based on their standard electrode potentials. For cations and anions the ease of discharge increases as you go down the list. What this means is that cations and anions lower in the list are the easiest to be discharged when there are more than one cation or anion present in a solution. So for instance if we have Cu^{2+} and Pb^{2+} ions in solution, Cu^{2+} would be preferentially discharged, leaving behind Pb ions in solution. If OH and NO$_3{}^-$ are in solution, which do you think would be preferentially discharged at the electrodes in electrolysis? I'll wait.

2. **Concentration of ions in Solution:** Even in situations where one species of ions may be preferentially discharged, we find that it happening that way is not always so. This happens because some ions are more concentrated than others in solution and hence these ones are preferentially discharged.

3. **Nature of the Electrodes:** Inert electrodes are electrodes that do not partake in the electrolytic process, in the sense that they do not influence electrolytic discharge. On the other hand electrodes like Platinum are known to be reactive

and hence actively influence what is being produced. This could be a determining factor in deciding or predicting ions that are deposited in the process.

Electroplating

In industrial applications, it can be quite difficult to produce and process pure metals. Things get expensive pretty fast and manufacturers have to consider more economical methods to produce the exact (or close enough) metals and materials with the properties they desire. For instance, a lot of 'gold' out there really isn't gold at all, so sometimes your mother may put on glistening 'golden' earrings that are not gold, but have simply undergone *electroplating*.

"Electroplating is defined as the process by which one metal is coated with or dissolved into another by the process of electrolysis."

With electroplating materials may be made to resist corrosion, be stronger, or just be made to be more attractive in appearance.

In electroplating the anode (positive electrode) is the metal that will be used to coat some other material. The cathode (negative electrode) is the object that would be coated. The electrolyte is a solution containing the metal that is doing the coating. When the process of electrolysis is allowed to run, the metal object is then covered with the electroplating material and becomes a different material. Quite delightful!

As usual, it is time for a refreshing beverage. I have taken to orange juices lately, they are quite healthy and great for thinking.

SUMMARY

- Electrolysis has a colourful history, with names like Michael Faraday, Rev. William Whewell, Anthony Carlisle, William Nicholson, Alessandro Volta, Humphry Davy and Luigi Galvani (You can read up on it sometime).

- The components to an electrolytic system are the electrolyte, the direct current, external circuit and the electrode.

- An electrolyte is a substance that produces free ions on dissolution in water.

- Electrolysis is defined as the process by which an electrolyte undergoes decomposition when an electric current is passed through it.

- Anodes are positively charged electrodes and cathodes are negatively charged electrodes.

- An electrochemical cell converts chemical energy to electrical energy.

- Arrherius' ionic theory states that when an electrolyte is dissolved or melted in water, its molecules dissociate into ions that move freely in solution.

- Ions are preferentially discharged at the electrodes due to reasons that include position on the electrochemical series, concentration of ions in solution and the nature of the electrodes.

- Electroplating is defined as the process by which one metal is coated with or dissolved into another by the process of electrolysis.

MNEMONICS

Found a mnemonic today?

- The reasons for preferential discharge of ions during electrolysis:

<p style="text-align:center">E   C   N</p>

E– Electrochemical; as in "Position of ions on the **electrochemical** series**.**"

C- Concentration; as in "**Concentration** of ions in solution**.**"

N- Nature; as in "**Nature** of the electrodes**.**"

'Eat Curly Noodles.' Or something else that's not about noodles.

REVISION QUESTIONS

1. Define the following:

a. Electrolysis

b. Electrodes

c. Electrochemical cells

d. Electroplating

2. State and explain the Ionic theory.

3. K^+ and Na^+ are both present in a solution during electrolysis, which would be discharged first and why?

4. Write the half-cell reactions for the following equation:

$$Ni_{(s)} + Hg_2^{2+} \rightarrow 2Hg_{(l)} + Ni^{2+}_{(aq)}$$
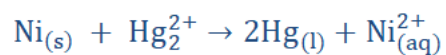
CHAPTER 9: THE PERIODIC TABLE

Groups and Periods

Well, hello again. We have been talking extensively about various elements on the periodic table but we haven't paused to consider how these elements occur and in what ways they relate to one another. In understanding these, the world of chemistry becomes crystal clear. In understanding the periodic table we begin to see how and why elements and compounds behave in the ways they behave. We study not just the physical attributes of these elements but their chemical characteristics as well. Enough talking, let's get right on the task. Below is the periodic table once more to aid us in our discourse.

Periodic Table of the Elements

I bet that being a sharp thinking person you must have at some point in our discussion wondered about the arrangement of the table. Are the elements placed at random locations or is there some method to the madness of this table of letters and numbers? Even though chemistry seems like madness, there are always precise reasons for all that we do as is characteristic of all sciences. For instance if you look up at the table you find that there are **rows** and **columns**. The rows move from one side to the next horizontally on the page, while the columns go up and down vertically on the page. The horizontal arrangement constitutes the **periods** while the vertical arrangement makes

the **groups** of the periodic table. Don't be fooled by the seeming simplicity of this table that looks more like a calendar because a lot of interesting things are going on here.

"The periodic table is an organized arrangement of chemical elements in rows and columns on account of increasing atomic numbers."

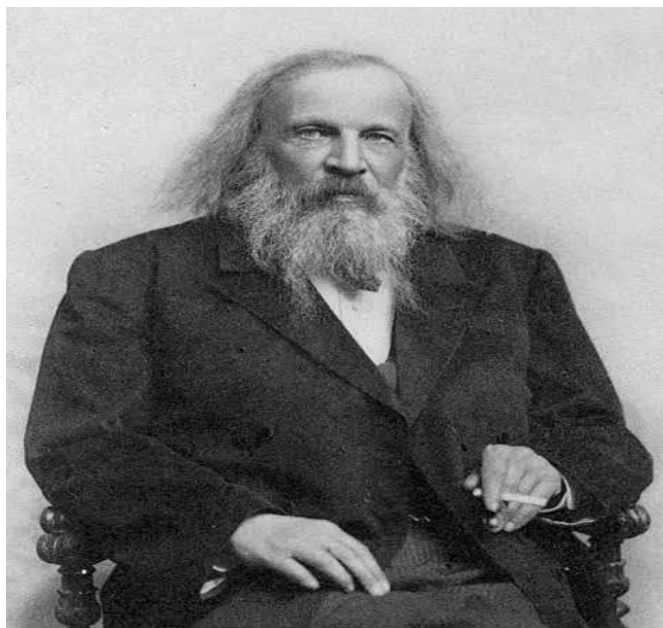This definition definitely brings something else to mind to consider and that is the concept of *atomic numbers.*

Figure 9-1 Dimitri Mendeleev

I know what you're thinking and even though we don't have to say it my big mouth will do just so-That is an intimidating looking man. Yes, yes he is but do not be carried away by how he makes you want to confess all your sins; be carried away instead by his brilliant and yes, intimidating mind for the man in the picture is none other than Dimitri Mendeleev the 'father' of the periodic table.

He didn't somehow birth the periodic table into existence the way we imagine reproduction in biological terms, but he did bring order into the disordered array of the grouping of elements. Being a renowned lecturer in Russia, he felt it his duty to write a chemistry text just like I am writing one except in his case he hadmore pressing reasons to (there were seldom any modern organic chemistry textbooks in Russian and the disordered elements gave him a headache). We can very easily picture him sitting at his desk, grouping and regrouping the elements like a weird jigsaw puzzle. We see him suddenly get up. Yes, that's an 'aha!' moment as he discovers that when grouped
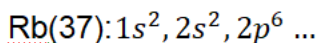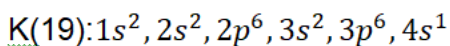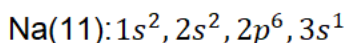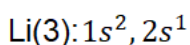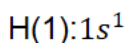
according to their atomic numbers the elements begin to show an interesting pattern and now he could even predict certain elements that have not even been discovered yet.

The Groups and the Periods

We have gone over a brief description of what groups and periods are. Now turn to the periodic table and look at it once more. What element begins the first group? I'll wait. If you stated hydrogen, you'd be right. Under hydrogen we find Li, Na, K, Rb, Cs and Fr (Look at the table to see what the symbols mean). The second group begins with Beryllium(Be) then Mg, Ca and so on. You could keep going until you reach the last group that begins with He. Have you observed that elements with the smallest atomic numbers begin the groups and those with larger atomic numbers are found down the group? Hold on to this observation and let's move on.

What about periods? H and He stand alone so let's take a look at the next element Li which starts the second period, followed by Be, then B, C, N, O, F and Ne. If we check period 3 we find Na, Mg and so on. Can you see that the atomic numbers also increase across the period?

Let's zoom in a little on what's going on in the background. We have learnt about electronic shells and configurations. I am certainly glad we studied that because that would make understanding this a breeze. If we study the group 1 elements we notice something interesting.

$H(1): 1s^1$

$Li(3): 1s^2, 2s^1$

$Na(11): 1s^2, 2s^2, 2p^6, 3s^1$

$K(19): 1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 4s^1$

$Rb(37): 1s^2, 2s^2, 2p^6 \ldots$

We don't need to finish writing down the configuration for the entire group, as I am quite certain you've noticed the pattern here as well. If you look closely, you find that the valence electrons (you recall the meaning) are exactly the same for each element in the same group. Here we see that the number of valence electrons for the elements of group 1 is 1. If we proceed to writing down the electronic configurations of the elements of group 2 we find a similar pattern. All the elements have 2 valence electrons each. Why not try writing them down? I'll wait.

I am quite sure you have seen the pattern with your own eyes. We can now safely say that *elements in the same group have the same number of valence electrons.*

Periods

Now that we have understood what basic factor determines group arrangement let's take a look at periods. You must recall what shells are. They dertermine the arrangement iof elements in groups. For instance elements in period 2 have 2 electron shells (K and L). Elements in period 4 have 4 electron shells(K, L, M, N). How many electron shells do elements in period 3 have?

In addition to shells we also find a pattern with regards their valence electrons.

$Li(3): 1s^2, 2s^1$

$Be(4): 1s^2, 2s^2$

$B(5): 1s^2, 2s^2, 2p^1$
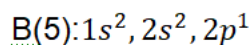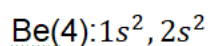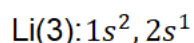
Notice how the number of valence electrons increases by one with each element? Li has 1, Be has 2 and B has 3; yes, 3. Don't be confused by the number '1' hanging above '2p'. The number of valence electrons is actually a combination of them meaning 3.

How Atomic Properties Become Clearer with the Periodic Table

Just like people have different properties that make them who they are, atoms are different too. Just like you have people of different shapes and sizes, atoms have different shapes and sizes too and just as people react differently to things, atoms are different when placed in certain conditions. These differences are also clearly seen when we look at the periodic table. Mendeleev did that in his groupings and we are going to take a look at them too.

Sizes (Atomic Radii)

We have already mentioned that the number of valence electrons increase as we move down the group of the periodic table. This could also translate to saying that the number of valence shells increase as well. It just makes sense. Imagine having a birthday party for twelve people. It is logical that you set out twelve seats to accommodate the twelve people. If however you realize that more people would be attending your party you set out more seats depending on the number of people that would be coming. So the

number of seats increases with the number of guests expected. The same goes for the group elements. As the number of electrons increases down the group, the number of valence shells increases so as to accommodate the increasing number of electrons. In the end we find that the atomic size increases as well so that the last element in the group would be larger than the first. Knowing this, it is now no surprise that the atomic size of Radium (Ra) is larger than Beryllium(Be).

If you understood what was just explained we can proceed to explain atomic and ionic sizes in the context of **electron clouds** (which is a more modern take on atomic structure which we have previously examined).

Unlike the neat little mental picture we painted with valence shells, electron clouds are little more difficult to picture. It is difficult to come to terms with their specific sizes but we take into account relative distances between nuclei using x-ray diffraction studies. The same can be said for *ionic sizes* which are just atomic sizes that undergo changes due to electron transfer i.e. when the atom loses or gains electrons. Down the group the electron cloud enlarges due to a reduction in the force of attraction between the positive charge of the nucleus and the electrons farther from it. The increasing number of shells however does not allow for a reduction in atomic size since they are farther away from the positive charge.

For the period however, the sizes of the atoms *decreases* progressively as we move from one element to the other from left to right. This is because the increasing number of electrons means an increase in the positive charge. This in turn means that the positive charge pulls in the electrons to itself even more allowing for a more 'compact' atom size. Unlike groups that extra shells are added, the number of shells across the period remains the same.

Electronegativity

We have discussed electronegativity before now but there's of course no crime in briefly having another look. You recall that electronegativity is the tendency of an atom of an element to accept electrons. Certain atoms such as Na have only one electron on their valence shells and hence they tend to give electrons and not accept. Na is therefore not electronegative, but *electropositive* because it easily gives the electron more than it accepts electrons. An atom of Fluorine however has 7 electrons on its valence shell and hence needs only 1 electron to complete the octet configuration and attain stability. F_2 can therefore be said to be electronegative. In the periodic table, electronegativity tends

to decrease as you go down the group due to the fact that atomic radii increases. Can you explain why this is so? I'll wait.
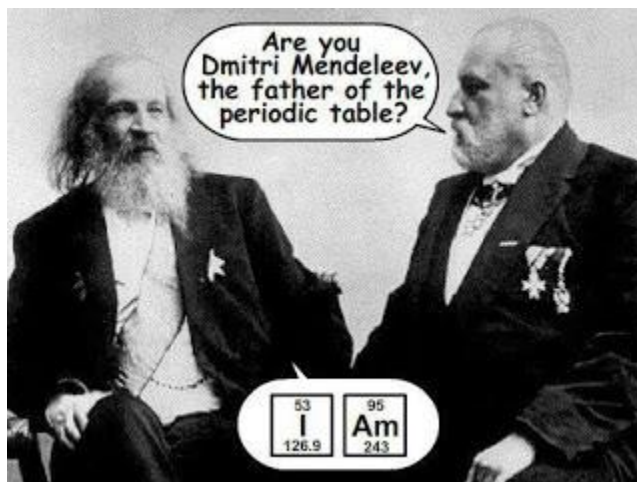

Figure 9-2 I chuckled a little

If you have been following (and I believe you have), you would understand that as the atomic radii increases down the group, there is more space on the shells for electrons. Lower number of electrons on the valence shells means that the corresponding atom would be quite far from an octet configuration, and hence more willing to lose electrons to reach that configuration, than accept electrons on its shells.

But what happens to electronegativity across the period? Well it increases across the period from left to right. This happens because the atomic sizes decrease as we proceed in that direction. In this case you have more electrons present on an average valence shell as you move from left to right. These usually need about one or two electrons to complete the octet configuration and hence are willing to accept electrons.

Electron Affinity

Electron affinity generally means the readiness of an atom or other elementary particle to accept electrons. Don't be confused by thinking **electronegativity** and **electron affinity** are the same thing. While electronegativity is the tendency to accept electrons, electron affinity is the energy released when an electron is added to an atom to form an ion (an anion). From this definition it is quite possible for you to guess what the periodic table trend is for this. Did you come to see that it must therefore increase across the period? Since more electrons are on the valence shells, the tendency to accept electrons would increase from left to right as more atoms would need one or two electrons to complete their octet configurations. It also largely decreases down the group for reasons I am certain you are aware of now.

THE GROUPS
## Group 1(Alkali Metals)

Chemical Properties

1. Due to their single valence electrons they show similar chemical reactions.

2. This single valence electron makes them highly electropositive (able to lose electrons) and hence very reactive.

$$K \rightarrow K^+ + e^-$$
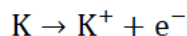
3. Their reactivity however differs, as elements down the group are more reactive than preceding elements. This is because as we proceed down the group the number of shells increases making the valence electrons move further from the nuclear charge and hence readily able to be removed. In addition to this, the *screening effect of inner electrons* allows for further distancing of valence electrons from the nuclear charge. This screening effect occurs when surrounding electrons repel each other due to having the same charge (negative). This makes the attractive force between the electrons and the nuclear charge weakens, making it easy for them to be removed from the shells; hence reactivity is said to increase down the group.

4. Since reducing agents give out electrons readily, it is safe to say that group 1 elements are good reducing agents. For the same reasons described above, their strength as reducing agents increases as we go down the group.

5. They readily react with water to form metal hydroxides and H.

$$2Na_{(s)} + 2H_2O_{(l)} \rightarrow 2NaOH_{(aq)} + H_{2(g)}$$
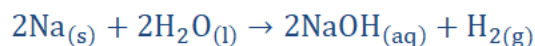
6. They react with chlorine (Cl) to form metal chlorides.

$$K_{(s)} + Cl_{2(g)} \rightarrow 2KCl_{(aq)}$$
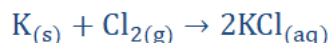
7. They generally react with group 7 elements also known as the *halogens* (we're getting there) to form metal halides. The general form for this reaction is;

$$2A + H_2 \rightarrow 2AH$$
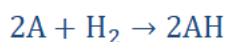
Where A: group 1 element and H is the halide, making AH the metal halide formed as a product of the reaction. Note that chlorine is a halide as well.

Physical Properties

1. They are usually referred to as *soft solids* as they are malleable and can be cut with ease.
2. They can conduct heat and electricity easily.
3. They don't seem to react well to the open air unlike you and I (perhaps) because they turn dull when exposed to air.
4. They have low boiling and melting points.
5. They are grey solids and can appear silvery when cut.
6. Their densities are comparably low compared to other metals.
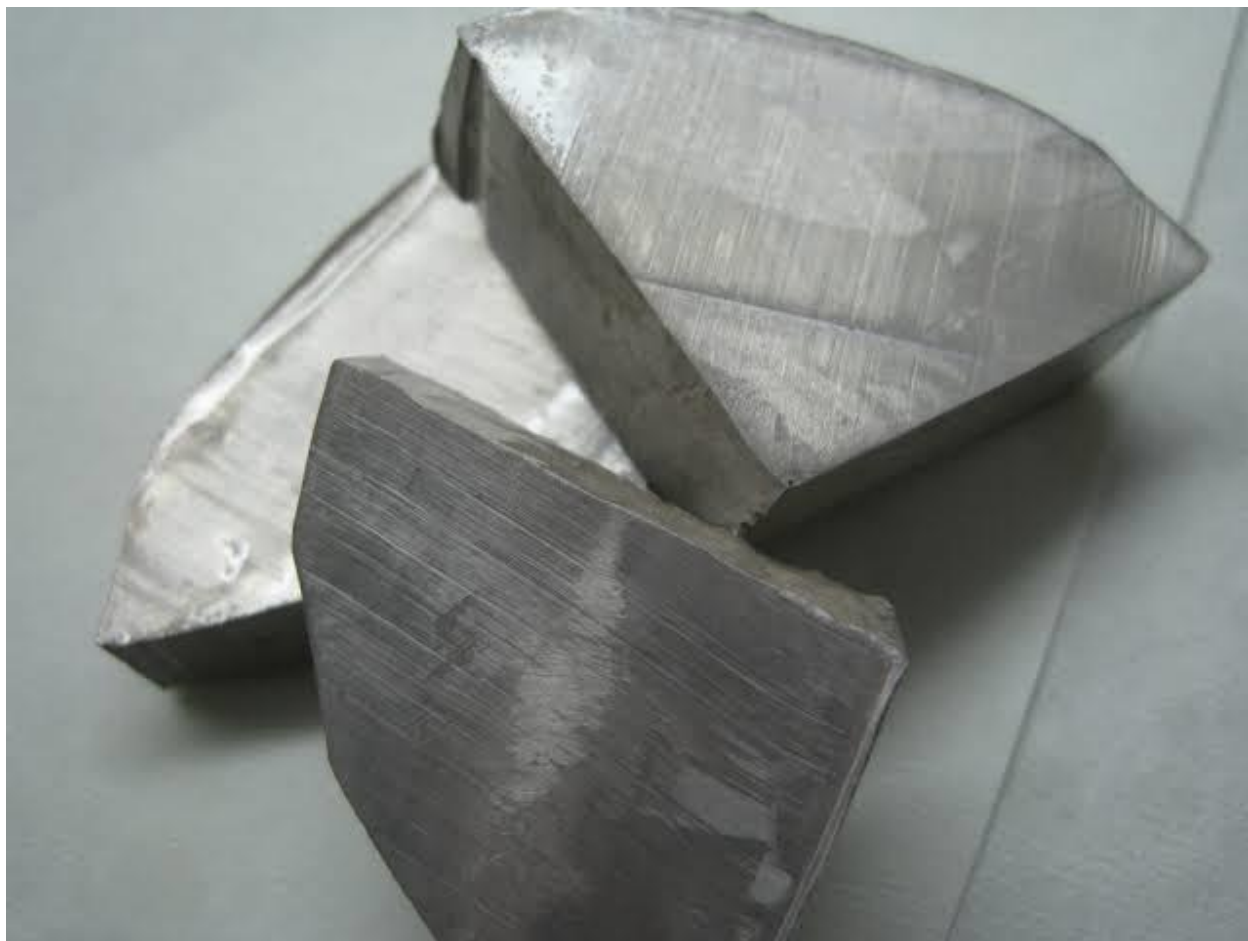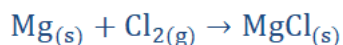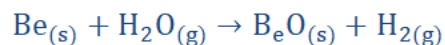

Figure 9-3 Na; a group 1 element

Group 2(Alkali-Earth Metals)

Chemical Properties

1. They react with the halogens to form metal halides, just like the group 1 metals do.

$$Mg_{(s)} + Cl_{2(g)} \rightarrow MgCl_{(s)}$$

2. On reacting with water, they tend to produce metal hydroxides and evolve hydrogen gas. Be however does not follow this trend as it does not react with water.

$$Be_{(s)} + H_2O_{(g)} \rightarrow B_eO_{(s)} + H_{2(g)}$$

3. They could react with Nitrogen to produce nitrides. This reaction must occur in conditions of high temperature.

$$Ba_{(s)} + N_{2(g)} \rightarrow Ba_3N_{2(aq)}$$
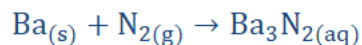
4. When they react with oxygen, they form oxides.

$$2Ca_{(s)} + O_{(g)} \rightarrow 2CaO_{(s)}$$
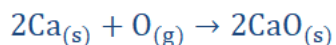
Physical Properties

1. Even though they appear 'soft'. They are harder than group 1 metals. However don't go biting down on either of them if you value your life.
2. They are electropositive and this increases down the group.
3. They are highly conductive both thermally and electrically (please don't bite down on them).
4. They have higher melting and boiling points in comparison to the alkali metals.

Figure 9-4 Beryllium metal

The Transition Metals

The transition metals are the elements that exist in the upper blocks of groups 3 to 12. It would be helpful to note that these elements are not the lower separated blocks under the groups, but the higher ones. This would become clearer in time so don't fret.

Properties

1. They have high boiling points

2. They can be very hard
3. They can be used as good catalysts
4. They show metallic luster
5. They can be very malleable (arts and crafts anyone?)
6. They typically have low ionization energies
7. They conduct electricity well
8. They have high melting point

Figure 9-5 Transition crafts anyone?

Group 13
Properties

1. They have three valence electrons in their outermost shells.
2. They form electrovalent/ionic compounds
3. They form amphoteric oxides and hydroxides (both acidic and basic properties)
4. They are softer and hence more malleable (does this remind you of another group?)
5. They have low melting points
6. They are not very conductive

Figure 9-6 Gallium melts in your hands

Group 14

Properties

1. They are tetravalent; meaning they have four valence electrons ('tetra' meaning four.)
2. Reactivity decreases down the group.
3. C, Si and Gm are not affected by diluted acids and water
4. Sn and Pb are amphoteric in nature.
5. Even though Pb and Sn are less reactive than the others, they are still able to react with the halogens (group 17 elements).
6. There are two oxidation states present in this group. While the +2 oxidation state increases as we move down the group, the +4 oxidation state decreases as we proceed down the group from C to Sn.

Figure 9-7 Carbon is quite an interesting element

Group 15
Properties
1. The density of the elements increase as we move down the group. N for instance is a gas, in the middle of the group we find metalloids such as As and then finally we find metals such as Bi.

2. There is an increase in atomic and ionic radii as we move down the group for reasons earlier explained. However, the increase from As to Bi is only relatively slight. This happens because of the presence of completely filled f or d orbitals in the more dense elements.

3. Since the atomic size increases as we slide down the group, electronegativity naturally decreases and we both know why.

4. The ionization energy as we move down also decreases since the atomic radii increases. If you remember clearly what *ionization energy* is you know that this has something to do with the nucleus having a weaker hold on the electrons.

5. There is an increase in boiling point down the group.

6. Allotropes of the elements exist except for N. (Allotropy is the ability of an element to exist in different physical forms but in the same chemical state. Water for instance has the gaseous (steam), liquid and solid (ice) allotropic forms while still having the same chemical state (two hydrogen atoms, one oxygen atom per molecule))

Figure 9-8 Antimony is an interesting name

Group 16

Properties

1. They are also known as *chalcogens.*
2. They are electropositive
3. Ionization energy and electron affinity decrease as we move down the group.
4. The atomic radii increase down the group
5. Metallic character increases down the group
6. Melting and boiling points increase down the group with increasing atomic numbers

Figure 9-9 Mined Sulphur

Group 17

Properties

1. These are known as the *halogens* or *salt formers*
2. They have seven valence electrons in their valence shells
3. They are coloured; the colours become darker as we go down the group, with F_2 being pale yellow, white or even colourless and I_2 being blue/black.
4. Their molecules are diatomic
5. They have low melting and boiling points due to weak van der waals forces holding their atoms together.
6. They are weak conductors of heat and electricity
7. They have low densities and hence are all non-metals.
8. Their reactivity decreases as we go down the group so that Cl_2 is more reactive than Br_2 which is more reactive than I_2 and I_2 more than At_2 (you get the picture).
9. They are highly electronegative
10. There is a gradation in their states as F_2 and Cl_2 are gaseous, Br_2 is a liquid and I_2 and At_2 are solids at room temperature.

Figure 9-10 Astatine

Group 18

Properties

1. These are the *rare* or *noble* gases (picture a serene unreactive yoda floating in midair as a visual aid)

2. They have no colour, odor or taste (yum)

3. Their atomic radii increase as we go down the group

4. They are gasses at room temperature

5. They generally have low melting and boiling points and their melting and boiling points increase down the group.

6. They have low densities and are insoluble in water

7. They do not conduct electricity and conduct heat only a little.

8. Noble gasses have a duplet configuration and this allows them to be very stable

9. They are *inert* in that they do not engage in reactions by moving their electrons about (in accepting, giving away or sharing). This makes them unreactive.

10. They are generally non-flammable.

Figure 9-11 Helium is used to fill balloons of all shapes and sizes

Lanthanides and Actinides

Lanthanides

Properties

1. These elements are the first of the two separated blocks of elements below the transition elements that are situated between groups 4 and 18 on the periodic table.

2. The first element from left to right is lanthanum and since they have similar properties they are all referred to as lanthanides.

3. They are generally silver coloured.

4. They are very reactive elements.

5. They are also known as *rare earths.*

6. Their atomic numbers varies from 57 to about 71.

7. Their densities increase down the group. They can be relatively soft though.

8. They have high melting and boiling points

9. They can burn in air fairly easily

10. They are good reducing agents.

Figure 9-12 Cerium

Actinides

Properties

1. They are called *Acting elements* and range in atomic number from 89 to 103.

2. They are located in the last row below the lanthanides; the first element from left to right is *actinium* and their similar properties have given them the name actinides.

3. Their isotopes are unstable and they are all radioactive so it's safe to treat them with caution.

4. They spontaneously ignite in air hence they are said to be pyrophoric.

5. Like the lanthanides, they are also quite soft. This makes them easily malleable.

6. They are very electropositive.

Figure 9-13 Plutonium

It is good to note that the lanthanides and actinides are often referred to as the *inner transition elements.* They seem to be the odd ones out and are separated from the rest of the family because they just can't seem to quite fit in. If they did fit in they would make the table unnecessarily difficult and cumbersome (Imagine this table but in 3d) Since we would like to sleep well tonight we would skip the reason for this separation, even though I encourage you to read up on it on your own if your merciful teachers would allow a scheme that could give you a little leg room for that.

Well, that was definitely an interesting find. And it's all thanks to Mendeleev else it would have been majorly difficult to make the many discoveries we continue to make now on account of the periodic table. Remember to give old Mendeleev a little thanks as you sip your drink and prepare to read some summaries and enjoy some practice questions- the best part ☺

SUMMARY

- The periodic table is an organized arrangement of chemical elements in rows and columns on account of increasing atomic numbers.

- The elements on the periodic table are divided into **groups** and **periods**. Groups consist of the vertical arrangement of elements from top to bottom, while periods include the horizontal arrangement from left to right.

- Dimitri Mendeleev, a brilliant Russian lecturer discovered the periodic table of elements.

- Factors such as **electronegativity, electron affinity** and **atomic radii (size)**determine the arrangement of elements on the periodic table.

- There are 18 groups in the periodic table (1 to 18, including the transition elements) though some texts show groups 1 – 0 (0 being group 18, representing the noble gasses, not including the transition elements) where we have groups 1,2,3,4,5,6 and 7. However this is an older method and is not largely in use anymore.

- The lanthanides and actinides are heavy elements located at the lower portion of the table.

- Group elements have similar characteristics.

MNEMONICS

What seems mnemonic worthy today? Look through the text and see if you can find any. Remember to keep it simple so it's easy to remember.

REVISION QUESTIONS

1. What is the periodic table?

2. Who is considered to be the father of the periodic table

3. Explain the following with regards to periodic table trends:
   a) Electronegativity
   b) Electron Affinity
   c) Atomic radii

4. List 5 properties each of the following groups:
   a) Group 1
   b) Group 2
   c) Group 13
   d) Group 14
   e) Group 15
   f) Group 16
   g) Group 17
   h) Group 18
   i) Transition Elements
   j) Lanthanides
   k) Actinides

5. For group one elements like H, how many valence electrons are on the valence shell?

Periodic Table of the Elements

Group																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

1 **H** Hydrogen 1.01

3 **Li** Lithium 6.94 — 4 **Be** Beryllium 9.01

11 **Na** Sodium 22.99 — 12 **Mg** Magnesium 24.31

19 **K** Potassium 39.10 — 20 **Ca** Calcium 40.08 — 21 **Sc** Scandium 44.96 — 22 **Ti** Titanium 47.88 — 23 **V** Vanadium 50.94 — 24 **Cr** Chromium 51.99 — 25 **Mn** Manganese 54.94 — 26 **Fe** Iron 55.85 — 27 **Co** Cobalt 58.93 — 28 **Ni** Nickel 58.69 — 29 **Cu** Copper 63.55 — 30 **Zn** Zinc 65.38

37 **Rb** Rubidium 85.47 — 38 **Sr** Strontium 87.62 — 39 **Y** Yttrium 88.91 — 40 **Zr** Zirconium 91.22 — 41 **Nb** Niobium 92.91 — 42 **Mo** Molybdenum 95.95 — 43 **Tc** Technetium 98.91 — 44 **Ru** Ruthenium 101.07 — 45 **Rh** Rhodium 102.91 — 46 **Pd** Palladium 106.42 — 47 **Ag** Silver 107.87 — 48 **Cd** Cadmium 112.41

55 **Cs** Cesium 132.91 — 56 **Ba** Barium 137.33 — 57-71 Lanthanide — 72 **Hf** Hafnium 178.49 — 73 **Ta** Tantalum 180.95 — 74 **W** Tungsten 183.85 — 75 **Re** Rhenium 186.21 — 76 **Os** Osmium 190.23 — 77 **Ir** Iridium 192.22 — 78 **Pt** Platinum 195.08 — 79 **Au** Gold 196.97 — 80 **Hg** Mercury 200.59

87 **Fr** Francium 223.02 — 88 **Ra** Radium 226.03 — 89-103 Actinide — 104 **Rf** Rutherfordium [261] — 105 **Db** Dubnium [262] — 106 **Sg** Seaborgium [266] — 107 **Bh** Bohrium [264] — 108 **Hs** Hassium [269] — 109 **Mt** Meitnerium [278] — 110 **Ds** Darmstadtium [281] — 111 **Rg** Roentgenium [280] — 112 **Cn** Copernicium [285]

5 **B** Boron 10.81 — 6 **C** Carbon 12.01 — 7 **N** Nitrogen 14.01 — 8 **O** Oxygen 16.00 — 9 **F** Fluorine 19.00 — 10 **Ne** Neon 20.18

13 **Al** Aluminum 26.98 — 14 **Si** Silicon 28.09 — 15 **P** Phosphorus 30.97 — 16 **S** Sulfur 32.06 — 17 **Cl** Chlorine 35.45 — 18 **Ar** Argon 39.95

31 **Ga** Gallium 69.72 — 32 **Ge** Germanium 72.63 — 33 **As** Arsenic 74.92 — 34 **Se** Selenium 78.97 — 35 **Br** Bromine 79.90 — 36 **Kr** Krypton 84.80

49 **In** Indium 114.82 — 50 **Sn** Tin 118.71 — 51 **Sb** Antimony 121.76 — 52 **Te** Tellurium 127.60 — 53 **I** Iodine 126.90 — 54 **Xe** Xenon 131.29

81 **Tl** Thallium 204.38 — 82 **Pb** Lead 207.20 — 83 **Bi** Bismuth 208.98 — 84 **Po** Polonium [209] — 85 **At** Astatine [210] — 86 **Rn** Radon 222.02

113 **Nh** Nihonium [286] — 114 **Fl** Flerovium [289] — 115 **Mc** Moscovium [289] — 116 **Lv** Livermorium [293] — 117 **Ts** Tennessine [294] — 118 **Og** Oganesson [294]

2 **He** Helium 4.00

Lanthanide

57 **La** Lanthanum 138.91 — 58 **Ce** Cerium 140.12 — 59 **Pr** Praseodymium 140.91 — 60 **Nd** Neodymium 144.24 — 61 **Pm** Promethium 144.91 — 62 **Sm** Samarium 150.36 — 63 **Eu** Europium 151.96 — 64 **Gd** Gadolinium 157.25 — 65 **Tb** Terbium 158.93 — 66 **Dy** Dysprosium 162.50 — 67 **Ho** Holmium 164.93 — 68 **Er** Erbium 167.26 — 69 **Tm** Thulium 168.93 — 70 **Yb** Ytterbium 173.06 — 71 **Lu** Lutetium 174.97

Actinide

89 **Ac** Actinium 227.03 — 90 **Th** Thorium 232.04 — 91 **Pa** Protactinium 231.04 — 92 **U** Uranium 238.03 — 93 **Np** Neptunium 237.05 — 94 **Pu** Plutonium 244.06 — 95 **Am** Americium 243.06 — 96 **Cm** Curium 247.07 — 97 **Bk** Berkelium 247.07 — 98 **Cf** Californium 251.08 — 99 **Es** Einsteinium [254] — 100 **Fm** Fermium 257.10 — 101 **Md** Mendelevium 258.10 — 102 **No** Nobelium 259.10 — 103 **Lr** Lawrencium [262]

Legend: Alkali Metal · Alkaline Earth · Transition Metal · Basic Metal · Metalloid · Nonmetal · Halogen · Noble Gas · Lanthanide · Actinide

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